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# EVALUATING PROTECTIVE ACTIONS FOR CHEMICAL AGENT EMERGENCIES

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## ABBREVIATIONS, ACRONYMS AND INITIALISMS

| | |
|---|---|
| ACH | air changes per hour |
| ANAD | Anniston Army Depot |
| ANSI | American National Standards Institute |
| AP | Associated Press |
| APG | Aberdeen Proving Ground |
| CAS | Chemical Abstract Service Number |
| CLEAR | Calculates Logical Evacuation and Response model |
| CSDP | Chemical Stockpile Disposal Program |
| Ct | atmospheric concentration multiplied by time |
| D2PC | Army dispersion code (computer model) |
| DHHS | Department of Health and Human Services |
| DOD | U.S. Department of Defense |
| EBS | Emergency Broadcast System |
| $ECt_{50}$ | statistically derived concentration-time integral where 50% of reference population are expected to exhibit observable effects (Effective Concentration multiplied by Time) |
| EIS | environmental impact statement |
| EPA | U.S. Environmental Protection Agency |
| EPRI | Electrical Power Research Institute |
| EPZ | emergency planning zone |
| ETE | evacuation time estimates |
| FEMA | Federal Emergency Management Agency |
| FPEIS | Final Programmatic Environmental Impact Statement |
| FSAR | Final Safety Analysis Reports |
| GA | chemical nerve agent (tabun) |
| GB | chemical nerve agent (sarin) |
| GD | chemical nerve agent (soman) |
| H | chemcial blister agent (mustard) |
| HD | chemical blister agent (distilled mustard) |
| HT | chemical blister agent (distilled mustard and an inorganic compound) |
| I-DYNEV | origin-to-destination route selection model |
| $ICt_{50}$ | statistically derived concentration-time integral where 50% of reference population are expected to suffer incapacitating effects (Incapacitating Concentration multiplies by Time) |
| IRZ | immediate response zone |
| LBAD | Lexington-Blue Grass Army Depot |
| $LCt_{50}$ | statistically derived concentration-time integral, that is lethal for 50% reference population (Lethal Concentration multiplied by Time) |
| MASSVAC | a probabilistic dynamic traffic assignment model |
| NAAP | Newport Army Ammunition Plant |
| NATO | North Atlantic Treaty Organization |
| NETVAC | a probabilistic dynamic traffic assignment model |

| | |
|---|---|
| OER | overall exposure reduction |
| PAECE | Protective Action Evaluator for Chemical Emergencies |
| PARDOS | partial exposure calculation code (computer model) |
| PAZ | protectiver action zone |
| PBA | Pine Bluff Arsenal |
| PUDA | Pueblo Depot Activity |
| RER | relative exposure reduction |
| RTMAS | Real-time Traffic Monitoring and Analysis System |
| SCBA | Self-contained breathing apparatus |
| TAP | toxicological agent protection |
| TEAD | Toole Army Depot |
| TRAFLO | traffic simulation model |
| TWA | time-weighted average |
| UMDA | Umatilla Depot Activity |
| UPI | United Press International |
| VX | chemical nerve agent |

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Carol Griffith-Davies collected the qualitative data that detail the current use of in-place shelters for chemical hazards presented in Appendix D. In addition, she was a participant observer in the expedient shelter trials summarized in Appendix F.

William Clevenger supervised the expedient shelter trials summarized in Appendix F. He assisted with the development of the qualitative instruments and maintained the integrity of the qualitative and quantitative data.

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## ABSTRACT

In the process of completing a Congressionally mandated destruction of the U. S. stockpile of unitary chemical weapons, the U.S. Army decided that enhanced emergency planning was needed to reduce the consequences of an accidental release of agent. In cooperation with the Federal Emergency Management Agency, other federal agencies, and affected state and local governments, the U.S. Army is in the process of implementing an enhanced emergency preparedness capability.

This research supports that effort by developing a method of evaluation for the principle protective action alternatives–evacuation, in-place shelter, and respiratory protection. In addition this research examines these alternatives for a limited set of scenarios to both "validate" the method's utility, and make some preliminary program recommendations regarding protective action strategies.

A model was developed to examine the effect various protective actions have on expected exposure under a variety of release and meteorological conditions. The model compares the expected exposure without protection, with the expected exposure given a specified emergency response system, and the capacity of the selected protective action to protect (assuming that all people to be protected have implemented the protective measure). These exposure estimates are graphically displayed over time from the beginning of the event in the context of their anticipated acute human health effects.

This report analyzed a total of 1134 scenarios–504 evacuation, 378 in-place sheltering, and 252 respiratory protection scenarios. This preliminary analysis focused on 14 classes of accidents (i.e., 5 GB, 5 VX, and 4 H/HD), for a range of meteorological condition (involving winds averaging 1, 3, and 6 m/s), and for a series of downwind distances (3, 10, and 20 km). These 126 accident scenarios were examined for emergency responses involving evacuation (clearing the area in 1, 5, 10, and 20 min), in-place shelter (expedient, enhanced and pressurized shelters), and respiratory protection (NATO civilian and U.S. military standard masks). All of the scenarios examined assumed that the protective actions would be implemented in the context of a state-of-the-art emergency response system. Such a system is characterized as being able to (1) detect and assess an accident, communicate that to off-site officials and make a decision to warn the public in five minutes or less; (2) have both indoor and outdoor emergency warning systems, such as siren and telephone ring-down systems; (3) stimulate public response at a rate that is 25% faster than previous disasters (empirically documented), including response to five chemical evacuations.

This analysis indicates that whenever there is enough time to complete an evacuation prior to a plume's impact, evacuation is the preferred alternative for most people in areas likely to be impacted by potential accidents. Because of the time it takes a plume to traverse 10 km even under moderate wind speeds evacuation is a viable option under most circumstances for areas 10 or more km from the source. In-place shelters are most appropriate in circumstances where time to respond is severely limited. In these cases pressurized shelters provide the maximum protection. Respiratory protection measures may be used to significantly reduce exposure in any accident, however, leakage around the filtration devices remains the dominant technical factor in the use of respiratory devices. Hence, respiratory protection is most likely to be considered appropriate when used in conjunction with either evacuation or reduced infiltration in-place shelters. Continued analysis of protective action effectiveness is required, both to determine the optimum protective action alternatives for specific areas, and provide recommendations regarding program standards for emergency planning.

Executive Summary

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## ES.1 INTRODUCTION AND BACKGROUND

Emergency preparedness measures can reduce the risks of adverse health effects of accidents involving the unitary chemical agent stockpile; however, evaluating which protection measures to select and how much they are likely to reduce exposure remains problematic. How can emergency managers determine which protective actions are best suited for response to hazard(s) presented by the chemical agent stockpile? Which populations are most appropriately protected by what measure? Will the same protective measure be effective for populations in all accidents? Historically, these judgments have been based on experience with previous disasters and the experience of others. Recent research supports these judgments; some have involved modeling to examine specific weak points and build on existing strengths. In addition, there have been three major thrusts of research regarding chemical hazards:

a. research regarding the physical ability to protect affected groups,
b. research concerning the behavioral aspects of emergency response, and
c. research on human health effects.

Analyzing the physical aspects of protection has focused on characterizing the nature of the hazard as well as the design/development of equipment and actions to physically reduce the degree of impact. Evaluating behavioral response to disasters has focused on various aspects of individual and social organizational response to disaster. Analyzing potential human health effects is by far the most extensive body of research and has concentrated on acute toxicity. This research attempts to integrate these three perspectives as they apply to the unitary chemical stockpile.

This report develops a conceptual model for evaluating protective action strategies and presents a preliminary analysis of some planning accidents. The model characterizes chemical agent emergencies in terms of the accident, the dispersion of any resulting release, and the associated human health consequences. The model also summarizes public response to the emergency in terms of the probability that a selected protective action will be implemented at a particular time, given the emergency response system to engender the implementation. The evaluation is made by comparing the expected population exposure: (1) unprotected; (2) protected by the selected action; and (3) the maximum protection a given action can achieve. The model allows emergency planners

to simulate the results of potential accidents combined with various protective action strategies so that a distribution of response options can be developed.

The objective of this research is to develop a method that characterizes the available protective actions for chemical hazards in the context of credible accidents in order to:

a. assist emergency managers in selecting the best combination of protective actions, affording optimum protection for the population at risk,
b. use real-time data (in the event of an accident) to assist emergency managers in making decisions regarding appropriate protective actions during chemical agent emergencies, and
c. randomly simulate realistic accident conditions, emergency exercise scenarios, the responses taken, and their associated consequences.

In addition to these three objectives, a system that evaluates the effectiveness of various protective action strategies in the context of the complete emergency response system makes it possible to determine the relative importance of each emergency response function (e.g., accident assessment, decision making, warning). Analysis along these lines helps determine what emergency planning efforts are needed in these areas so as not to seriously jeopardize the ability of the recommended protective measure to effectively reduce exposure.

## ES.2 EVALUATING PROTECTIVE ACTIONS

Conceptually, the effectiveness of any particular action taken to protect people in the event of a chemical accident depends on its ability to reduce chemical exposure to tolerable levels and the probability that the people to be protected take the action in a timely manner. Two factors that determine an action's ability to reduce exposure to tolerable levels: the degree of hazard or amount of toxic agent present in the unprotected environment, and the protective action's ability to either reduce or avoid that exposure. The timeliness may be thought of as a function of the amount of time it takes for a toxic plume to travel a given distance, compared with the time it takes the emergency response system to get people at that distance to protect themselves from or avoid harm.

Protective actions need to be examined in the context of potential accidents, the complete emergency response system, and the associated environment. This research develops a model of emergency response effectiveness that characterizes (1) potential accidents as they are likely to occur, (2) the complete emergency response system that leads to the implementation of the protective action, and (3) those parts of the environment that significantly affect either the character of the accident or the nature of the response, or both. This approach puts the evaluation of the effectiveness of each protective action in the context of the identified potential for harm and the comprehensive emergency response system.

Two basic considerations underlie the effectiveness of each protective action. First is the inherent ability of each measure to avoid or reduce exposure. Hence, capacity to protect or avoid includes only the physical ability of the action to protect or avoid. For example, the ability of a respiratory device to protect is dependent upon (1) the efficiency

of the charcoal filter in removing airborne chemicals and (2) the degree to which leakage around the filters can be prevented. This physical capacity of the protective action to provide protection determines the maximum exposure reduction that people using it can achieve.

The second consideration is the amount of time required to complete a given action, because a protective measure can reduce exposure only when it is implemented. The completion of a protective action involves the time it takes (1) to detect the hazard, assess the situation, and decide a warning is appropriate; (2) to disseminate the warning message that both alerts people to the potential for harm and notifies them concerning appropriate responses; (3) for the public to decide on an appropriate course of action; and (4) for people to implement the selected action. This timing determines the extent of exposure prior to the complete implementation of the protective action.

In the process of developing a system to evaluate the effectiveness of protective actions, several guiding principles were used.

- Flexibility: any system of evaluation to be useful must be flexible enough to accommodate the potential situations to be evaluated.
- Empirically based: to be useful, any system of evaluation must be based on reality; one way to obtain this reality is to build in data, conclusions, and knowledge from existing research.
- Parsimony: any system of evaluation is a representation of the complete process; such systems focus on the main elements of the situation, those parts of the system that fundamentally alter the outcomes.
- Modularity: any system of evaluation must be able to accommodate changing information, knowledge and methodologies over a period of time. Modular development allows critical elements to be extracted from the system and replaced with new components.
- Uncertainty and precision: the precision of an evaluation resulting from a system should be commensurate with the amount of uncertainty in the system and its components.

## ES.3 CONCEPTUAL APPROACH

The approach used to examine protective action effectiveness herein focuses on the ability of a selected action to reduce or eliminate exposure in the context of the emergency response system required to implement that protection. This method characterizes the emergency in terms of the accident, the dispersion of the resulting release, and the human health consequences associated with the resulting exposures. In addition, the approach summarizes the response to the emergency in terms of the probability that the selected protective action will be implemented at a particular time. Expected exposure is represented in terms of (1) the exposure that would be expected without protection, (2) the exposure given the probability that the selected protective action is implemented, and (3) the exposure given that the protective action is unconstrained by behavior (i.e., operating at its protection capacity). These expected exposure estimates are then compared with each other and the expected human health

consequences associated with exposure at that level. Figure ES.1.1 presents the conceptual framework for evaluating protective action effectiveness employed in this report.

This approach encompasses protection factors by examining the protection capacity of the protective actions for the specific release being considered. In addition, this approach encompasses the analysis of previous disaster research by employing the available data and research in the determination of the probability of implementing a specific protective action, but it is simultaneously not limited by the scope of the previous research. This approach is probabalistic in that estimates of expected exposure are based on the probability of completing the protective action, which depends on the entire emergency response system. This expected value method has the advantage of representing the expected exposure of a population rather well. However, it has the disadvantage of not representing the exposure of any particular individual. Hence, the expected exposure is the expected exposure multiplied by the probability of not completing the protective action, plus the probability of completing the action multiplied by the protected exposure. Suppose, for example, that at a particular time in the emergency the exposure without protection is 10 $mg/m^3$ and the probability of completing a protective action is 0.2, or two people completing for every eight that have not completed the action. Further, suppose that the action under consideration completely avoids exposure—protection capacity equals zero. Hence, expected exposure is 0.8 _ 10, or 8 $mg/m^3$ during that period and none of them received an 8-$mg/m^3$ exposure. In fact, two received no exposure at all, while eight were exposed to 10 $mg/m^3$.

In meeting the conceptual objectives of developing a method for evaluating protective action alternatives, this report is characterized by two central thrusts: the model development and the preliminary analysis using the model. The development of the evaluation model involves two aspects: (1) the analysis of existing data and research required to determine the relevant input for the model and (2) the actual development of the model accomplished by specifying the relationships among relevant elements. The preliminary analysis has two central purposes: (1) to validate the model and (2) to provide initial insight concerning protective action alternatives that are not viable. These twin purposes are evidenced throughout this report.

## ES.4 ESTIMATING EFFECTIVENESS

One of the principal concerns of this research involves the physical ability of various protective actions to reduce exposure to chemical agents. Protection capacity assumes that all behavioral or response functions are adequately performed to ensure design criteria performance of protective measures. Protection capacity, therefore, does not take into consideration the proportion of the population or number of people having been warned, deciding to respond, and implementing the specified respiratory device. The protection capacity is the sum of the reduced concentrations from the beginning of the accident to time t, where t is any moment during the accident.

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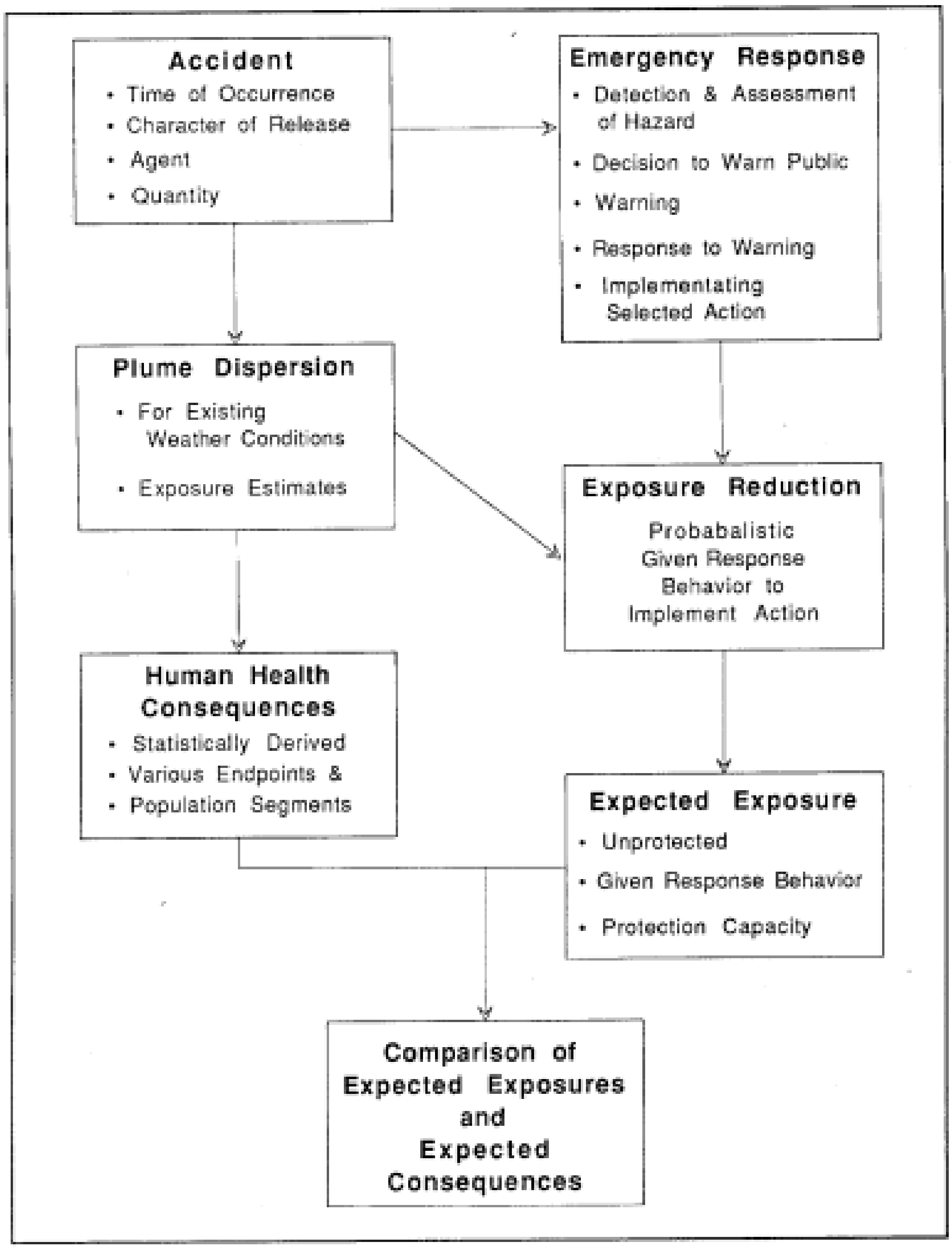


Fig. ES.1. Conceptual framework for evaluating protective action effectiveness.

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### ES.4.1 Protection Capacity

For a respiratory device the ability to reduce exposure is a simple function of leakage around the device and penetration through the filter, known as breakthrough. For a respiratory device characterized by leakage, L, and breakthrough, B, the protection capacity is calculated as a direct function of L and B, and the concentration of agent, in the unprotected environment. For any moment, t, the protection capacity of a respiratory device is expressed as the expected concentration while using a given respiratory device,

$$C_p = (1 - b)\, C_u\, L + b\, C_u\ ,$$

where $C_u$ is the concentration of chemical in the unprotected environment at t, L is leakage, and b is equal to 1 if the sum of $C_u$ exceeds the breakthrough standard B at time t; otherwise, b is 0. The first part of the binomial represents the leakage prior to reaching the breakthrough standard, and the second part of the binomial accumulates the entire unprotected concentration once the breakthrough standard is reached.

For in-place shelters, the ability to reduce exposure depends on the amount of infiltration from the unprotected environment to the protected environment and the difference in concentration between the protected and unprotected environments. For any moment, t, the protection capacity of an in-place shelter is expressed as the expected concentration in the protected environment,

$$C_{pt} = C_{pt-1} + I\, (C_{ut-1} - C_{pt-1})\ ,$$

where $C_p$ and $C_u$ are as previously defined, I is the infiltration rate in period t, and $C_p$ is the amount of agent in the protected environment at the beginning of the period. This formulation allows for the mixing of fresh (noncontaminated) air into the protected environment as the plume passes by and $C_u$ becomes smaller than $C_p$ at the same rate, I, at which it became contaminated as the plume arrived.

For evacuation, the reduced concentrations are a simple function of the proportion of the population completing evacuation and the concentration of agent in the unprotected environment. The protection capacity associated with evacuation for any moment t is expressed as the expected concentration given the probability of completing the evacuation at time t,

$$C_p = (1 - P(e))\, C_u\ ,$$

where $C_u$ is the unprotected concentration and P(e) is the probability of completing evacuation. Unfortunately, the completion of evacuation is not completely separable into the physical or structural aspects and the behavioral or response elements. While evacuation time is clearly a function of driving behavior, it is also a function of structure (e.g., carrying capacity of roads, maximum attainable speeds of vehicles). In theory, if all road networks were large enough to handle all evacuation traffic, then exposure reduction capacity for evacuation would be complete (i.e., no exposure would be received); however, because the times at which evacuations can be completed are both structural and

behavioral, the exposure reduction capacity for evacuation can exceed zero. The protection capacity may also be expressed in terms of exposure at time t as

$$Ct_{p,} \Sigma C_{pt}.$$

### ES.4.2 Response-Adjusted Exposure

To reflect accurately the effectiveness of a protective action, the measure must reflect the probability of implementing the action. Expected exposure for a given population at time t is calculated as

$$E(C_p) = (P(i)\ C_p) + (1 - P(i))\ C_u\ ,$$

where P(i) is the joint probability of having reached a decision to warn, receiving warning, deciding to respond, and implementing that response at time t, and $C_p$ and $C_u$ are the protected and unprotected exposures, respectively. The expected concentration-time integral accumulates the expected concentration $E(C_p)$, from time zero to t, to represent the cumulative exposure, Ct, anticipated for a population protected by protective action i. This expected exposure in the protected environment is a probabilistic measure of population exposure for the given protective action.

### ES.4.3 Model Overview

The protective action support model is conceptually comprised of a number of modules that address specific parts of the problem of protective action decision making. Conceptually the model consists of those modules characterizing the nature of the hazard and its consequences and the modules that characterize emergency response. Each module is linked with the adjacent modules in the process. An overview of the Protective Action Evaluator for Chemical Emergencies (PAECE) is presented in Fig. ES.2. PAECE begins with the specification of the initiating events in terms of the time and nature of the accident resulting in a release. The time of the release determines (1) the time at which the emergency response begins, (2) the distribution of people in various locations, and (3) the likelihood of the occurrence of various meteorological conditions.

Each module in the emergency response process characterizes another step in the process that attains public response. The warning diffusion module characterizes warning system effectiveness in terms of the probability of receiving warning at various times in the process. The response decision module characterizes the public's decision to respond to the warning message in terms of public response to previous chemical emergencies. The protective action implementation module characterizes the implementation of various protective actions in terms of probability of completion once the decision to respond is made. The probability of a completed protective action is the joint probability of having (1) public officials decide to warn, (2) the public receiving the warning, (3) the population at risk deciding to respond, and (4) the implementation of the protective measure. Such a joint probability accounts for the time each emergency response step takes.

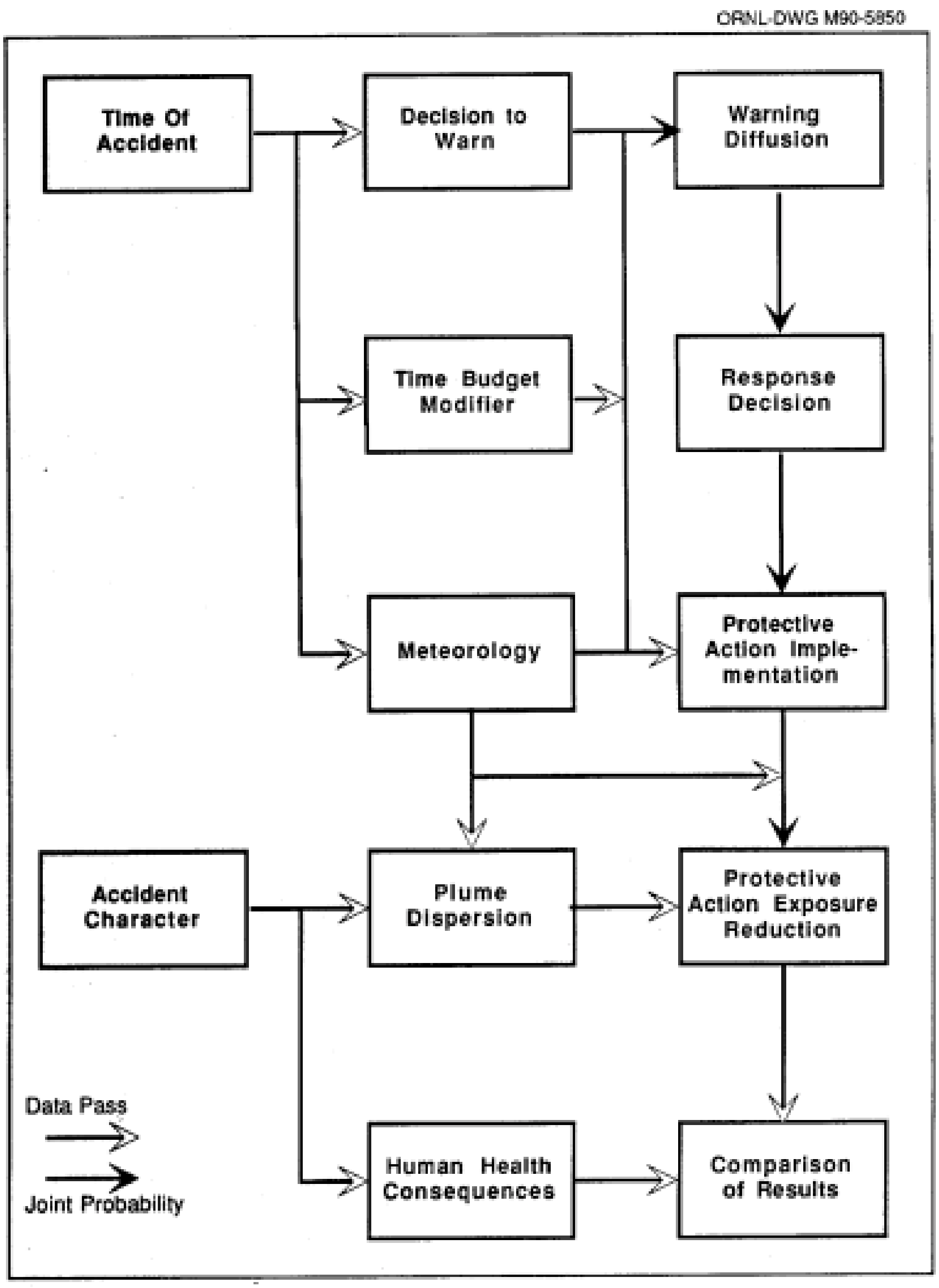


Fig. ES.2. Conceptual model of protective action evaluation for chemical accidents.



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Accident characterization in terms of the type and amount of agent released, together with the meteorological characterization, allows the estimation of plume dispersion for given downwind distances. These data alone determine concentrations of agent in the unprotected environment. In addition, the type of agent allows selection of the appropriate anticipated human health impacts for comparison with the estimated unprotected and protected exposures.

## ES.5 EVACUATION

Evacuations involve a series of organizational and individual or family decisions. At the individual or family level, the decisions include (1) whether to evacuate, (2) when to evacuate, (3) what to take, (4) how to travel, (5) route of travel, (6) where to go and (7) when to return. The nature of these decisions help illustrate the fact that evacuation is a complex social process and not a stimulus-response event. While these decisions are being made, considerable communication and social interactions occur. As a result, evacuation planning is not a perfect science and at times is a highly politicized topic.

The preliminary analysis presented herein evaluated four evacuation scenarios for the 14 classes of accidents representing the distribution of accidents, for three downwind distances (i.e., 3 km, 10 km, and 20 km) and three meteorological conditions (i.e., winds of 1, 3 and 6 m/s with stability class F, D and C respectively), resulting in 504 release/response scenarios.

The response scenarios are considered "goal-oriented" because they are consistent with the assumption that a state-of-the-art emergency response system is available and in use at each location. Hence, emergency response scenarios assume that (1) a decision to warn is made in 5 min, (2) a combination warning system is used which is comprised of sirens for outdoor warning and a telephone ring-down system for indoor warning, and (3) the public responds 25% faster than they responded in the Confluence, Pennsylvania, train derailment.

Evacuation is summarized in terms of a time associated with clearing an area at risk to areas far enough away to be considered safe. One way to conceptualize this is in terms of the time it takes to arrive at a safe distance. This approach typically characterizes evacuation clearance times on the basis of evacuation time estimates (ETEs). ETEs are scheduled for the emergency preparedness program associated with the CSDP, but have not yet been conducted. Hence, a range of clearance time assumptions can be used to evaluate the effectiveness of protection achieved with evacuation. Hence, the evaluation of 5-, 10- and 20-min clearance times represent the range of ETEs believed to be acceptable for various segments of the population. In addition, a 1-min clearance time is used to represent a nonconventional approach that is similar to being able to outrun the leading edge of the plume. All evacuation scenarios accumulate the concentrations present at the distance to be evacuated until an evacuation is complete and a safe distance is reached.

The preliminary analysis indicates that evacuation is a viable option at distances over 10 km. Fatalities are unlikely under any scenario. In catastrophic accidents, given windspeeds of 3 m/s or greater, evacuation is unlikely to be effective at 3-km distances. In other situations, a comparison of evacuation with other actions seems warranted before

a protective action recommendation is made for populations within 10 km. At distances under 10 km, evacuation is most appropriate under stable weather conditions, with low winds speeds. However, because fatalities are still likely to occur, a comparison of protective actions seems to be warranted for any scenario.

## ES.6 IN-PLACE SHELTER

In-place protection involves the reduction of air exchange between the exterior toxic environment and the interior sheltered environment. The degree to which the flow of potentially contaminated air flows into the shelter can be used to generally characterize the type of in-place protection.

Extensive energy conservation research has shown that air exchange in most U.S. dwellings is distributed from fairly leaky units at about 1.5 air changes per hour (ACH) to the more tightly sealed units at 0.5 ACH. These rates have been shown to be related to windspeed, orientation to the wind, structural characteristics, and temperature difference between the indoor and outdoor environments.

The amount of protection afforded by shelters of various exchange rates is examined and related to the actions required to achieve them in the emergency time period. Three basic alternatives are examined: pressurized, enhanced, and expedient shelters. Pressurized shelters are characterized as a special case where there is no exchange of air from the unprotected to the protected environment (0.0 ACH). Enhanced shelters are weatherized structures where the air exchange between interior and exterior environments is reduced. Because these structures are weatherized in advance of the accidental release of chemicals, they can be assumed to have low exchange rates (0.5 ACH) and require only that doors and windows be closed to achieve the desired level of protection. Expedient shelters can achieve further reductions in air exchange (represented here as 0.2 ACH) but require more time to implement procedures to achieve the maximum protection.

Assuming a goal-oriented emergency response system, these three in-place shelter alternatives are examined for the 14 release scenarios, for three downwind distances (i.e., 3 km, 10 km, and 20 km) and three meteorological conditions (i.e., winds of 1, 3, and 6 m/s with stability class F, D and C respectively), resulting in 378 release/response scenarios.

In-place protection is summarized in terms of three basic cases involving infiltration rates of 0, 0.2 and 0.5 ACH. Normal sheltering in leaky dwelling units (1.5 ACH) was not considered in this analysis because (1) it is inconsistent with the goal oriented approach being taken here; and (2) in cases where normal sheltering will be effective, enhanced will also be effective. Hence, normal sheltering can be further examined in those instances where enhanced shelters are effective to determine the impact of such a planning decision. Implementation of pressurized and enhanced shelters involves only the closing of doors and windows.

When situations characterized by adverse health effects are anticipated, evacuation of an area is preferable to in-place shelter when it can be completed prior to impact. The preference for evacuation is based on two fundamental characteristics of in-place sheltering contrasted with evacuation; first, while a portion of the exposure continues after implementation of in-place shelters, exposure is avoided completely when the people are evacuated; second, shelters that reduce but do not eliminate infiltration of toxic agents will

have to be vacated once the plume has passed to afford maximum protection. No "second-step" is required of evacuation. Shelters that reduce infiltration of toxics can also increase the expected exposure in the sheltered environment if they are not vacated when the plume passes. For example, plumes that would not be expected to exceed the $LCt_{50}$ for a population can be augmented by slow implementation and improper ventilation of the shelter upon the passage of the plume.

In-place protection characterized by reduced infiltration provides limited protection in long-duration events because of the character of the exchange rate that simply allows a portion of what is in the unprotected environment into the sheltered environment. Hence, over long-duration releases, in-place shelters downwind will continue to accumulate agent concentrations under conditions in which even fairly small concentrations of agent augment significantly over relatively short durations. Hence, in-place shelters characterized by 0.5 ACH exchange rate can be recommended in response to small continuous releases, for relatively short durations. Protective action decisions involving larger releases or those with unknown or long durations should avoid exposure via evacuation if possible.

It is inappropriate to recommend enhanced shelters alone because of the additional protection afforded by implementing expedient measures within enhanced shelters. It is much more effective to take advantage of the rapid implementation of enhanced shelters and to augment them with the reduced infiltration of expedient shelter procedures for an interior room. This approach to protection in-place affords a moderate degree of protection quickly and can be followed with greater protection upon completion of the taping and sealing of the interior room. Hence, by curtailing exposure early in the period through rapid implementation and limiting continued exposure later in the emergency due to the reduced infiltration associated with taping and sealing an interior room, a combined method provides optimum protection among the in-place measures that allow infiltration to continue (i.e., nonpressurized shelters).

## ES.7 RESPIRATORY PROTECTION

Individual respiratory protection involves the removal of agent prior to inhalation through the use of filtration devices. Respiratory devices that are specifically designed for use in chemical environs are generally characterized by the degree of leakage around the device or seal and the amount of agent that can be absorbed before the filter capacity is exceeded. The two characteristics are referred to as leakage and breakthrough capacity, respectively.

Respirators are capable of providing excellent protection from inhalation exposure to aerosols and vapor. Respirators include a facepiece assembly fitted with filters to remove airborne toxic compounds. They do not supply air and are not intended for use in an oxygen-deficient atmosphere. Available facepiece designs provide varying degrees of protection to the eyes, face, and respiratory organs/tissues. A full-face design is evaluated in this analysis.

Filter elements are packed with activated charcoal that has been impregnated with salts of copper, silver, and/or chromium to augment the capacity of the filter to absorb or denature chemical agents. Filter capacity of a given filter at any given time is largely a function of storage conditions and regular maintenance/replacement of filter elements.

Two respiratory protection scenarios were evaluated for the 14 release scenarios for three downwind distances (i.e., 3 km, 10 km, and 20 km) and three meteorological conditions (i.e., winds of 1, 3, and 6 m/s with stability classes F, D, and C, respectively). A total of 252 release/response scenarios resulted. The response scenarios examined herein are considered "goal-oriented" because they are consistent with a state-of-the-art emergency response system. Less than 1 in 7 (15%) of the respirators used will leak around the filter. The efficacy of individual respiratory units fitted with two different filter elements was compared: the NATO civilian vapor standard for GA/GB at 3000 mg-min/$m^3$ and VX/vesicant at 1000 mg-min/$m^3$; and the U.S. military M17A1/M17A2 respirator filter standard of 159,000 mg-min/$m^3$.

The preliminary analysis assumes reasonably good implementation conditions in that full-face respirators are used by adults, and that 15% of the masks used will leak around the facepiece seal. This is considered a protective assumption because civilians faced with a chemical emergency, where respirator use is critical, would be likely to do without eyeglasses and make numerous other expedient decisions to improve facepiece fit. Expedient hood designs may also be employed in conjunction with respirator use. An M4 bubble periphery mask exhibited the best performance of all mask concepts tests, with 87.2% pass rate (plus or minus 5%) in self donned tests. Various designs of the XM40 mask provide self don results of 88 to 97% pass rates, depending on the amount of supervision, and the existence of a hood; however, the use of spectacles with these masks significantly reduced the ability to protect the wearer. Moreover, respiratory devices that leak in more than 15% of the applications would be unlikely to be recommended for public use as part of an effective emergency response program. To the extent that respiratory protection is considered a viable option, other respiratory alternatives for toddlers and/or infants will require appraisal. Several hood jacket and infant carrier designs equipped with battery-driven or passive filters are commercially available.

Breakthrough of the filter canister was determined to be a problem mostly for mustard scenarios that included use of NATO civilian-standard filters. In all other agent scenarios, fatal exposures for protected populations were the result of exposure via leaky respirator seals and the timing of warning, response, and implementation. The constant 15% leakage assumed in the preliminary analysis may be greater than what is likely during actual implementation among a public with heterogeneous facial configurations, facial hair patterns, and eyewear use. However, this analysis clearly points out the need for careful fitting, seal maintenance, and consideration of supplemental protection to reduce infiltration (such as the use of hoods in combination with a respirator). Moreover, this analysis suggests that even relatively small leakage rates can result in significant exposure when the concentrations are high or the plume is of long duration. Hence, any mitigation of the respirator seal problem will significantly reduce the potential for fatalities with this protective action. Respirators made available for civilian use should incorporate filter design specifications at least as stringent as the U.S. military-issue standard (i.e., Ct=159,000 mg-min/$m^3$).

Respiratory protection is effective within 10 km and most effective within 3 km. At 20 km, respiratory protection is unlikely to be required for protection of the public. Respiratory protection for individuals at 3 and 10 km lends itself well to combined approaches, where sheltering of various types or evacuation can be performed in

conjunction with respirator use. The maintenance and fitting requirements necessary for effective respirator use would be best served by institutional management and device ownership at the local level. Community health departments could handle the responsibility of training and fitting the protected population, distributing respiratory devices, and running periodic maintenance checks and drills.

## ES.8 CONCLUSIONS AND RECOMMENDATIONS

Table ES.1 summarizes the preliminary conclusions associated with this goal-oriented analysis. This research confirms that for the 1.2 million people living more than 10 km but less than 35 km away from storage facilities the preferred protective action is very likely to be evacuation. The analysis of evacuation scenarios for goal-oriented emergency response systems indicates that evacuation is a viable option for people located over 10 km from the source of agent release. This conclusion is generally driven by the amount of time it takes for a release to traverse 10 km (i.e., more than 2.5 h under 1-m/s winds or approximately 50 min under 3-m/s winds) under moderate and light winds, and the tendency to disperse significantly under winds of 6 m/s. The amount of time available at this distance generally provides enough time to implement an evacuation.

When situations are characterized by adverse health effects, and an evacuation of the area can be completed prior to the impact of a plume on an area, evacuation is preferable to in-place shelter alternatives. This arises in part because exposure continues for people within reduced infiltration in-place shelters after they are fully implemented and in part because such shelters will have to be ventilated or vacated once the plume has passed.

When either long-duration events or very high concentrations are considered, reduced infiltration in-place shelters provide only limited protection. Hence, to the extent possible, evacuation should be used whenever it can be completed prior to impact, or when avenues of egress are clearly not being affected by the plume. In-place sheltering is most appropriate in those cases where time to respond is severely limited. In these cases, pressurized shelters provide the maximum protection for those people within. Enhanced shelters could also be used to afford significant protection to people in close proximity; however, in situations characterized by adverse health effects, it would be inappropriate to recommend using enhanced shelters alone. Because of the additional protection afforded by implementing expedient measures within enhanced shelters, the proactive expedient activities should be undertaken as well.

Moreover, under conditions of relatively minor release, for example, characterized by a release with reversible health effects, reduced infiltration in-place sheltering can provide significant protection at minimal cost. These benefits are significantly increased when implementation is augmented by the current location of people in indoor locations (e.g., in the dead of night). But emergency planners will have to exercise considerable care in recommending such actions so that people can ventilate or vacate the in-place shelters once the plume has passed. Further, such measures are probably inappropriate in scenarios where the current "minor" release may become a long-duration or more extreme release situation. Hence, emergency managers would be ill-advised to recommend reduced infiltration in-place shelter when releases are not yet controlled (e.g., where the

Table ES.1. Summary of protective action recommendations

| Quantity released | Winds 1 m/s | Winds 3 m/s |
|---|---|---|
| **Less than 5 km distance** | | |
| Small | Shelter/Evacuation | NA[a] |
| Medium | Evacuation | Evacuation/ pressurized shelters |
| Large | Evacuation/ pressurized shelters | Pressurized shelters |
| **5 to 10 km distance** | | |
| Small | Evacuation | NA[a] |
| Medium | Evacuation | Evacuation/ respiratory protection |
| Large | Evacuation | Evacuation/ pressurized shelters |
| **More than 10 km distance** | | |
| Small | NA[a] | NA[a] |
| Medium | Evacuation | NA[a] |
| Large | Evacuation | Evacuation |

[a]Not applicable because these releases of GB, VX, and H/HD are unlikely to traverse this distance under these winds with exposures exceeding the $LCt_{50}$ for newborn infants.

fire is still burning) or where the plume may become a long-duration event because of meteorological conditions (e.g., during early evening hours, when winds may shift or become calm).

Emergency managers could augment each structure's ability to limit infiltration passively by having electrical power turned off in the area(s) likely to be impacted, which would automatically shut down whole-house circulating systems and reduce the amount of infiltration. One consequence of this action, however, would be that warning via electrical devices (e.g., radios and televisions) could be eliminated. In areas where telephone ring-down systems were being used to alert and notify the public, that system could give advance notice of the need to vacate or ventilate the in-place shelter.

To the extent that respiratory protection devices are used, emergency planners will have to expend considerable effort to limit exposure associated with leakage around the filtration system of the device. This analysis clearly points out the need to carefully fit people expected to use these devices, undertake considerable maintenance programs to ensure continued viability, and consider the use of respiratory devices that will accommodate a variety of fit/seal problems associated with the general public. It also points out that respiratory protection must be implemented very quickly for it to be considered a viable option.

To provide acceptable protection from catastrophic releases of agent, emergency response will have to be rapid enough to get people to implement the action. One way to achieve more rapid response to public warnings is to provide the public with enough information to allow them to confirm the conclusion reached by the officials making the recommendation.

With the possible exception of worst-case events, which are characterized by very large releases under slow onset (1-m/s winds), the marginal benefit of using respiratory devices in conjunction with evacuation means that emergency managers may find it more useful to enhance their ability to detect, assess and make decisions, and communicate them to the public so that rapid implementation of evacuation can be achieved than to supply respirators to the public and maintain them once they are issued. Moreover, because pressurized shelters eliminate exposure, it is unnecessary to consider the use of respiratory devices in addition to pressurized in-place protection.

The common behavioral underpinnings for the exposure associated with both respiratory protection and reduced infiltration shelters, particularly enhanced sheltering, means that adding respiratory protection to in-place sheltering does not necessarily reduce exposure for the population as a whole. Hence, for large releases under rapid onset, pressurized shelters are more likely to provide acceptable protection than a combination of respiratory protection with reduced infiltration shelters. Moreover, when considered in conjunction with the supply, maintenance, and potential liability issues raised by the use of respiratory devices, pressurized shelters are likely to considered preferable.

# 1. INTRODUCTION

This analysis evaluates protective actions for safeguarding the public from chemical warfare agent emergencies before and during congressionally mandated destruction of the existing unitary chemical weapons stockpile. On-site destruction by high-temperature incineration was the alternative recommended by the Chemical Stockpile Disposal Program (CSDP) Final Programmatic Environmental Impact Statement (FPEIS) (U.S. Dept. of the Army 1988) and was the option ultimately selected by the Under Secretary of the Army in his Record of Decision on February 23, 1988 (Ambrose 1988). Accident analyses indicate that the likelihood of hazardous agent exposure to off-site populations during continued storage and the various stages of the disposal program is small. Nevertheless, the probability is not zero and emergency plans are essential to provide the public with maximum protection. This document quantifies, as well as possible, the degree of protection offered by an array of available actions under varying conditions of meteorology and emergency response scenarios.

Chemical hazards present a significant hazard to modern societies. The unitary chemical weapons stockpile represents one very specific variety of chemical hazard. For the on-site disposal option, the FPEIS estimates the probability of one or more fatalities for accidents involving the entire (continental U.S. unitary chemical) stockpile at $3.2 \times 10^{-4}$, or 3.2 chances in 10,000 disposal programs. The estimated probability of one or more fatalities for the continued storage of the unitary stockpile was estimated at $2.4 \times 10^{-3}$, or about 2.4 chances in 25,000 years (U.S. Department of the Army 1988). Moreover, the FPEIS estimates that the expected number of fatalities associated with the on-site disposal option are $9.4 \times 10^{-4}$, with continued storage of the stockpile being more than 400 times as risky ($4.5 \times 10^{-1}$). The mortality estimate for on-site storage seems to indicate that at least one fatality is expected if the no-action alternative is taken. The FPEIS includes estimates for the maximum number of fatalities associated with the on-site disposal alternative to be slightly over 5000, with the maximum number of fatalities for the continued storage alternative to be approximately 89,000 (more than 16 times greater) (U.S. Department of the Army 1988).

While it is generally agreed that emergency preparedness measures can reduce the risks of adverse health effects of accidents involving the unitary chemical agent stockpile, the selection of specific emergency preparedness alternatives remains problematic. How can emergency managers determine which protective actions (e.g., evacuation, in-place sheltering, or respiratory protection) are best suited for response to hazard(s) presented by the unitary chemical stockpile? Which populations are most appropriately protected by what measure? Will the same protective measure be effective for populations in all accidents? Historically, these judgments have been based on experience with previous disasters and the experiences of others. Recent research supports these judgments; some have involved modeling to examine specific weak points and to build on existing strengths (Drabek 1986; Pate-Cornell 1986; Glickman and Ujihara 1988; Lindell and Barnes 1986; Bellamy and Harrison 1988). In addition, there have been three major thrusts of research

regarding chemical hazards:

- research regarding the physical ability to protect affected groups,
- research concerning the behavioral aspects of emergency response, and
- research on human health effects.

Analyzing the physical aspects of protection has focused on characterizing the nature of the hazard as well as the design/development of equipment and actions to physically reduce the degree of impact. Evaluating behavioral response to disasters has focused on various aspects of individual and social organizational response to disaster. Analyzing potential human health effects is by far the most extensive body of research and has concentrated on acute toxicity. This research attempts to integrate these three perspectives as they apply to the unitary chemical stockpile.

## 1.1 BACKGROUND

### 1.1.1 Congressional Mandate

In December 1985, Congress directed the U.S. Department of Defense (DOD) to destroy the U.S. stockpile of lethal unitary chemical weapons in such a manner as to provide (1) maximum protection of the environment, the general public, and the personnel involved in the destruction; (2) adequate and safe facilities designed solely for the destruction of the stockpile; and (3) cleanup, dismantlement, and disposal of the facilities on completion of the disposal program (Public Law 99-145, DOD Authorization Act of 1986). This law affects only the unitary chemical weapons which contain a lethal agent at the time the weapon is loaded, not binary weapons which contain agent precursors that mix and react to form lethal agent after the weapon is fired. The act required that disposal of the entire lethal unitary stockpile be completed by September 30, 1994, but was amended in 1988 to permit operations testing of commercial-scale incinerator design on Johnston Atoll in the Pacific Ocean (U.S. Department of the Army 1983) and to allow for disposal to be completed by September 30, 1997. The CSDP was established in 1986 by the U.S. Army Toxic and Hazardous Materials Agency to accomplish this mission.

Although there are unofficial estimates of the size of the lethal unitary chemical weapons stockpile [e.g., 22,680 metric tons (Apt 1988) and 27,215 metric tons (Adams 1989)], precise details regarding its absolute quantity and composition are classified for national security reasons. The M55 rocket stockpile is the only part of the total stockpile that is not classified. As of December 31, 1983, there were 404,596 rockets, each containing approximately 5 kg of agent GB or agent VX. Other than the approximately 6% (combined total by agent tonnage) stored in the Federal Republic of Germany and on Johnston Atoll, the unitary stockpile is stored at the eight installations depicted in Fig. 1.1.

The largest single quantity (approximately 42% by agent tonnage) of the U.S. unitary chemical weapons stockpile is stored at Tooele Army Depot (TEAD), south of Tooele, Utah, and southwest of Salt Lake City. The smallest quantity (approximately 1.6%) is stored at Lexington–Blue Grass Army Depot (LBAD), near Richmond, Kentucky.

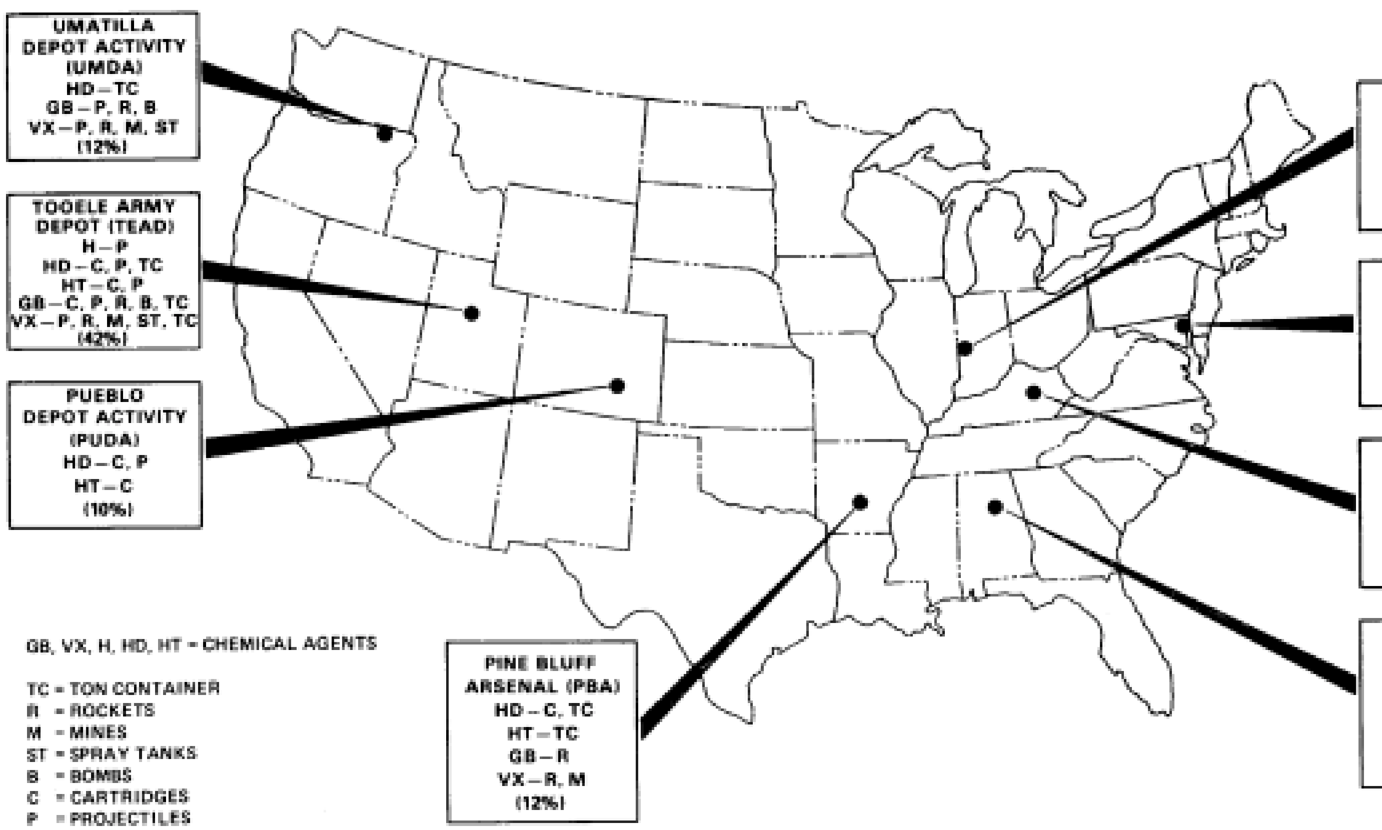


Fig. 1.1. Unitary stockpile distribution throughout the country. Note that small quantities of GA and Le are also stored at TEAD.

The Umatilla Depot Activity (UMDA), near Umatilla, Oregon; Pine Bluff Arsenal (PBA), near Pine Bluff, Arkansas; Anniston Army Depot (ANAD), near Anniston, Alabama; and TEAD have the most heterogeneous inventories in terms of both agent and munition type. Aberdeen Proving Ground (APG), near Edgewood, Maryland, and Pueblo Depot Activity (PUDA), near Pueblo, Colorado, store only mustard agent (in bulk containers at APG and in explosively configured munitions at PUDA). LBAD, APG, and the Newport Army Ammunition Plant (NAAP), near Newport, Indiana, have the smallest quantities of agent (less than 5% at each site). Only ton containers of VX are stored at the NAAP.

Although agents are stored in a variety of configurations, most (approximately 60% by agent tonnage) are stored in bulk as ton containers, spray tanks, and bombs. The explosively configured munitions (e.g., M55 rockets, M23 land mines, mortars, cartridges, and some projectiles) present a greater challenge for disposal because the separation of explosive materials from the agent is itself a hazardous activity. Explosively configured weapons are, by Army regulation, stored in earth-bermed bunkers or igloos. The only items stored in the open are ton containers of mustard agent.

### 1.1.2 Agent Characterization

Table 1.1 summarizes pertinent physical and biological characteristics of nerve agent. Table 1.2 summarizes the characteristics of vesicant agent. The stockpile inventory includes both organophosphate (nerve) and vesicant (blister) agents. The nerve agents include GA (tabun; "G" for German, identifying this agent as one found among German military stores captured at the close of World War II), GB (sarin), and VX ("V" for venom). Agents held in research and development quantities, such as the nerve agent GD (soman), are not considered part of the retaliatory stockpile (quantities are too small to be considered militarily significant) and are not included in the CSDP. The vesicant agents include H, HD, and HT (various formulations of sulfur mustard), as well as lewisite (L) (an organic arsenical). Each of these agents was formulated especially to cause major injuries or death to enemy forces in wartime and is acutely lethal at sufficiently high exposure. Table 1.3 documents agent control limits for maximum worker and public exposure. At or below these levels, no adverse health effects are expected. These exposure limits are based on values initially developed by the DOD but modified by recommendations arising from technical review by the Centers for Disease Control and several working groups convened by the U.S. Surgeon General [U.S. Department of Health and Human Services (DHHS)]. In the absence of federal regulations, these control limits establish standards for the safe handling and treatment of nerve and mustard agents during the disposal process.

## 1.2 OBJECTIVES

One of the problems facing emergency planning officials is the evaluation of the various protective actions available to protect the public from exposure to agent should an accidental agent release occur. Protective action decisions are particularly critical in making the appropriate response to chemical accidents. Emergency officials would prefer to evaluate the effectiveness of protective action before recommending them in response

Table 1.1. Characteristics of nerve agents[a]

| | GA | GB | VX |
|---|---|---|---|
| Common name | Tabun | Sarin | Mustard |
| CAS No.[b] | 77-81-6 | 107-44-8 | 50782-69-9 |
| Chemical name | N, N-dimethyl phosphoramidocyanidate, ethyl ester | Methyl phosphonofluoridate, isopropyl ester | S-(2-diisopropylaminoethyl) methyl phosphonothiolate, *o*-ethyl ester |
| Chemical formula | $C_5H_{11}N_2O_2P$ | $C_4H_{10}FO_2P$ | $C_{11}H_{26}NO_2PS$ |
| Vapor pressure (at 25°C) | 0.07 mm Hg | 2.9 mm Hg | 0.0007 mm Hg |
| Liquid density (at 25°C) | 1.073 g/cm$^3$ | 1.089 g/cm$^3$ | 1.008 g/cm$^3$ |
| Freezing point | -50 °C | -56 °C | -39 °C (calculated) |
| Color | Colorless to brown | Clear to straw to amber | Clear to straw |
| Mode of action | Nervous system poison | Nervous system poison | Nervous system poison |

[a]U.S. Department of the Army 1988.
[b]Chemical Abstracts Service number.
[c]Varies with sample purity.
[d]Agent T is bis[2(2-chloroethylthio)ethyl]ester; CAS No. 63918-89-8.
[e]At 20 °C.
[f]Varies $\pm$0.1 °C, depending on purity and isomers present.

Table 1.2. Characteristics of vesicant agents[a]

| | H, HD | HT | Lewisite |
|---|---|---|---|
| Common name | Sulfur mustard | Sulfur mustard | Lewisite |
| CAS No.[b] | 505-60-2 | Blend[d] | 541-25-3 |
| Chemical name | bis(2-chloroethyl) sulfide | 60% HD and 40% T[d] | Dichloro(2-chlorovinyl) arsine |
| Chemical formula | $C_4H_8Cl_2S$ | Blend[d] | $C_2H_2AsCl_3$ |
| Vapor pressure (at 25°C) | 0.08 mm Hg[c] (H)<br>0.11 mm Hg (HD) | 0.104 mm Hg | 0.58 mm Hg |
| Liquid density (at 25°C) | 1.27 g/cm$^3$ | 1.27 g/cm$^3$ | 1.89 g/cm$^3$[e] |
| Freezing point | 8-12 °C (H)<br>14 °C (HD) | 1 °C | -18 °C[f] |
| Color | Amber to dark brown | Amber to dark brown | Amber to dark brown to black |
| Mode of action | Blistering of exposed tissue | Blistering of exposed tissue | Blistering of exposed tissue |

[a]U.S. Department of the Army 1988.
[b]Chemical Abstracts Service number.
[c]Varies with sample purity.
[d]Agent T is bis[2(2-chloroethylthio)ethyl]ether; CAS No. 63918-89-8, $C_8H_{16}Cl_2OS_2$.
[e]At 20 °C.
[f]Varies $\pm$0.1 °C, depending on purity and isomers present.

**Table 1.3. Agent control limits recommended by Surgeon General's Working Group [Department of Health and Human Services (DHHS)][a]**

| Agent | Workplace an 8-h exposure at ($mg/m^3$) | General population a 72-h time weight average ($mg/m^3$) |
|---|---|---|
| H/HD/HT | $3 \times 10^{-3}$ | $1 \times 10^{-4}$ |
| GA/GB | $1 \times 10^{-4}$ | $3 \times 10^{-6}$ |
| VX[b] | $1 \times 10^{-5}$ | $3 \times 10^{-6}$ |
| Lewisite | $3 \times 10^{-3}$ | $3 \times 10^{-3}$ |

[a]Values recommended by Surgeon General's Working Group after review of pertinent data and documented in "Recommendations for Protecting Human Health and Safety Against Potential Adverse Effects of Long-Term Exposure to Low Doses of Agents GA, GB, Mustard, Lewisite and VX" 52 FR 48458 (December 22, 1987).

[b]Notice and request for public comment on VX values in 52 FR 19926 (May 28, 1987). Comment period closed July 29, 1987. Control limits recommended by DHHS to Secretary of the Army in October 1987.

to a chemical emergency. Each protective action provides a different level of protection depending on the type of accident. For example, accidents characterized by very rapid onset reduce the effectiveness of certain protective actions for populations in close proximity to the release, while accidents that result in a relatively small cloud of toxic chemicals (a "puff") can make other protective actions more effective. The problem for emergency managers may be thought of as either

- being able to recognize these differences, select appropriate protective actions, and communicate them to the populations that require protection in such a way that appropriate response is likely; or
- selecting a distribution of protective actions for people at various locations that optimizes protection for the complete array of accidents.

The latter would be preferable from a communication and response standpoint, because it simplifies communication and warning messages and facilitates more uniform response. It may not be desirable, however, for some segments of the population because

it can lead to inefficiencies when more obtrusive or costly protective actions are used consistently rather than less obtrusive or less costly measures that provide adequate protection.

This report develops a conceptual model for evaluating protective action strategies and presents a generic analysis of some planning accidents. The model includes hazard identification and assessment, airborne dispersion, organizational and community decision making, emergency warning, public response, implementation, and immediate recovery. The analysis attempts to partition the population at risk into those for which a single protective action is appropriate and those requiring multiple protective response measures. Population segments best served by single protective action strategies are characterized in terms of potential onset time, response implementation time, response vulnerability in terms of the response window, and the decision to implement. Population segments requiring multiple protective actions are examined also in terms of protective action decision making and the information required. The model allows emergency planners to simulate the results of potential accidents combined with various protective action strategies so that a distribution of response options can be developed.

The objective of this research is to develop a method that characterizes the available protective actions for chemical hazards in the context of credible accidents to

- assist emergency managers in selecting the best combination of protective actions, affording optimum protection for the population at risk;
- use real-time data (in the event of an accident) to assist emergency managers in making decisions regarding appropriate protective actions during chemical agent emergencies; and
- randomly simulate realistic accident conditions, emergency exercise scenarios, the responses taken, and their associated consequences.

The planning objective is aimed at the analysis of various protective actions in the response to credible accidents scenarios under a representative set of circumstances. From a planning perspective, the objectives consist of identifying those individuals who can always respond to an accident with a single protective action and those people who will require different responses for various accident release scenarios. For people adequately protected by a single protective action option, the identification of that action is the primary objective. For those people who require multiple responses, the identification of the conditions under which each protective action alternative is optional is required.

The emergency decision-making objective involves near-real-time evaluations of the most appropriate recommendation to protect the population for specific accidents as they evolve. Rapid results are essential. The response objective focuses primarily on the scenario and response to select the most appropriate alternative for populations where a single response fails to provide optimal coverage. To the extent that the critical response objective is met, the method also may be used to reevaluate the preliminary selection of appropriate protective actions for populations employing single responses.

The exercise objective involves the use of the protective action model to generate accident scenarios and potential emergency responses. The model also assists in the evaluation of exercise play.

In addition to these three objectives, a system that evaluates the effectiveness of various protective action strategies in the context of the complete emergency response system makes it possible to determine the relative importance of each emergency response function (e.g., accident assessment, decision making, and warning). An implicit objective of this research is to determine which emergency planning efforts are needed in these areas so as not to seriously jeopardize the ability of the recommended protective measure to effectively reduce exposure.

## 1.3 SCOPE AND LIMITATIONS

The stated objectives are very ambitious. In part, these goals cannot be met completely by this project alone. Although the objective is to develop tools that can assist emergency managers in making decisions concerning emergency planning, response, and management, the utility of any evaluation model rests with the locally responsible decision makers. As with any model, its use must be tempered with experience, good judgment, common sense, and a thorough understanding of the model's limitations.

Several specific limitations focus the research. First, while some of the findings, conclusions, and recommendations of this research may be applicable to emergency workers, employees, and military personnel within the confines of the installation, the focus of the analysis is on off-post civilian populations. In addition, the emphasis of this analysis is on the off-post areas that are most likely to be affected by accidental releases associated with the storage and destruction of the unitary chemical stockpile. Second, the analysis concentrates on areas where protective action decision making and alternative selection are not clear (i.e., areas in close proximity to potential source points and "transition" areas where recommendations are likely to change from one strategy to another). Third, this analysis considers only the plume exposure pathway. Ingestion pathways are not considered, and percutaneous exposure is treated in a very limited way. A preliminary evaluation of protective clothing is presented in Appendix A.

## 1.4 CONCEPTUAL APPROACH

There are a variety of ways by which the effectiveness of protective actions can be conceptualized. One way to evaluate the effectiveness of protective actions is to determine the protection factor of various protective measures. This approach focuses almost entirely on the physical attributes of the protective action or device. At least in this case the measurement of protection factors rests on data that are simply not available for all the protective actions that need to be considered and to provide protection from chemical agents. Appendix B examines the measurement and problems associated with protection factors.

Another way to examine protective action effectiveness involves the calculation of program costs (per lives saved). This alternative tends to assume that if protective actions are provided the public, then the public is protected. Moreover, initially using costs to determine effectiveness tends to put the emphasis on costs and undervalues the importance of providing protection, a tendency that is in direct opposition to the maximum protection requirement of Public Law 99-145 (DOD Authorization Act of 1986). By

emphasizing costs, the evaluation tends to focus on the device alone, rather than on the device, its use in the context of an emergency preparedness system, and (social) ramifications of preparedness. Furthermore, costs are directly attributable to specific manufacturers and usually for only brief durations. Hence, costs can be used to select from among protective action alternatives that provide equivalent protection.

A third way to examine protective action effectiveness involves the analysis of previous disasters of a similar nature. This approach can be very effective in providing "lessons learned" from previous experience. There are several excellent summaries of research on previous disasters (Drabek 1986; Mileti et. al 1975; and Dynes 1970) and specific areas such as evacuation (Sorensen and Mileti 1987), warning (Baker 1987; Janis and Mann 1977; Leik and Carter 1981; Mileti 1975; Perry and Mushkatel 1984; Rogers and Sorensen 1989; Rogers 1989; Sorensen and Mileti 1987) and specific disasters (Baker 1979; Burton et. al 1981; Gruntfest 1977; Perry and Greene 1983; and Sorensen 1987a). The limitations of this approach are linked directly to the disaster occurrences they analyze. First, these studies can only evaluate protective actions that are used in response emergencies; second, they can only determine effectiveness after the occurrence. The former limits the analysis to the examination of previously used protective actions and tends to focus the attention on evacuation which is the most often used preparedness measure. The latter is particularly important because of the unique nature of the unitary chemical stockpile and its extreme toxicity.

The approach used to examine protective action effectiveness herein focuses on the ability of a selected action to reduce or eliminate exposure in the context of the emergency response system required to implement that protection. This method characterizes the emergency in terms of the accident, the dispersion of the resulting release, and the human health consequences associated with the resulting exposures. In addition, the approach summarizes the response to the emergency in terms of the probability that the selected protective action will be implemented at a particular time. Expected exposure is represented in terms of (1) the exposure that would be expected without protection, (2) the exposure given the probability that the selected protective action is implemented, and (3) the exposure given that the protective action is unconstrained by behavior (i.e., operating at its protection capacity). These expected exposure estimates are then compared with each other and with the expected human health consequences associated with exposure at that level. Figure 1.2 presents the conceptual framework for evaluating protective action effectiveness employed in this report.

This approach encompasses protection factors by examining the protection capacity of the protective actions for the specific release being considered. In addition, this approach encompasses the analysis of previous disaster research by employing the available data and research in the determination of the probability of implementing a specific protective action, but it is simultaneously not limited by the scope of the previous research. This approach is probabilistic in that estimates of expected exposure are based on the probability of completing the protective action, which depends on the entire emergency response system. This expected value method has the advantage of representing expected exposure for a population. However, it has the disadvantage of not representing the exposure of any particular individual. Hence, the expected exposure is

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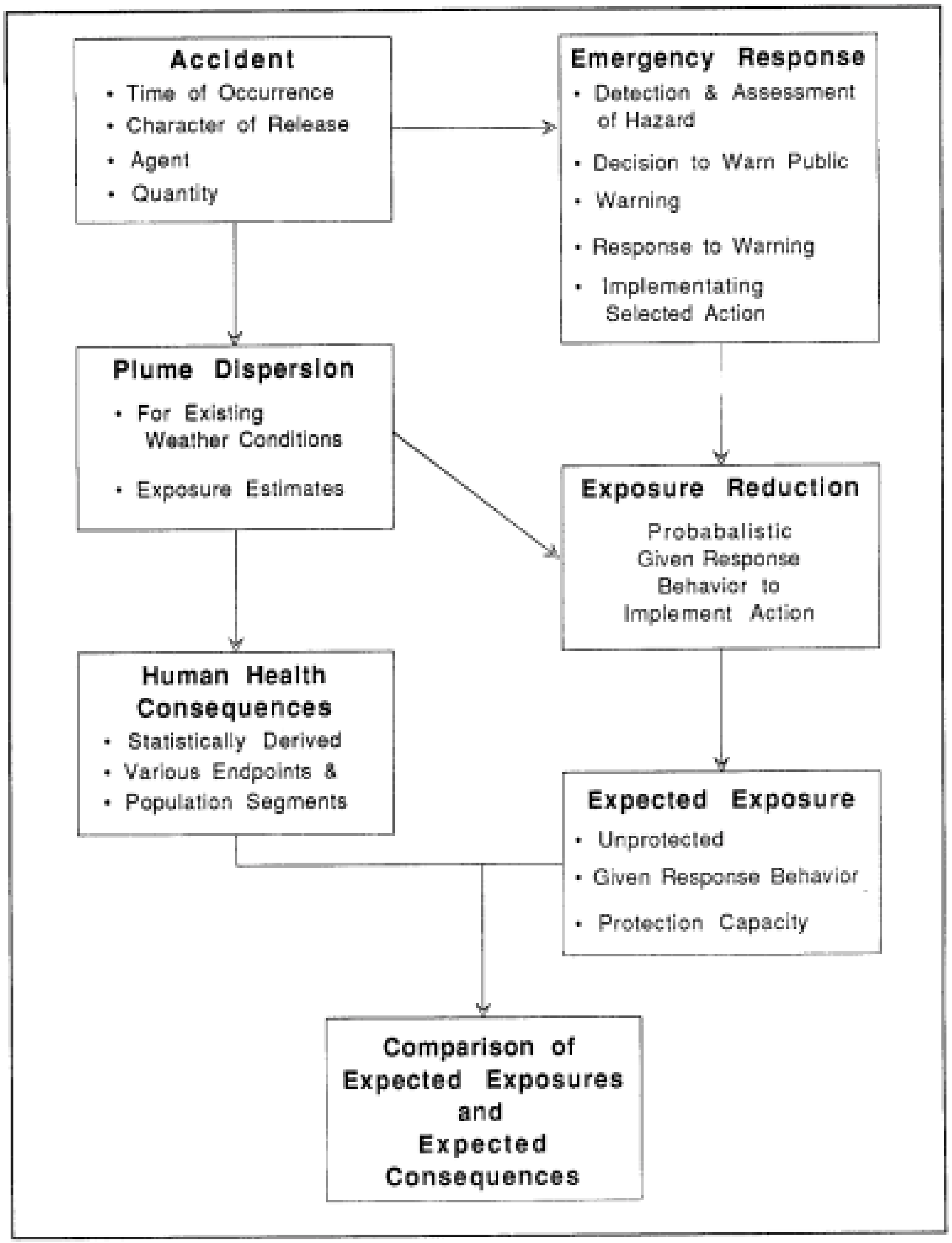


Fig. 1.2. Conceptual framework for evaluating protective action effectiveness.

actually the expected exposure without protection, times the probability of not completing the protective action, plus the probability of completing the action times the protected exposure. Suppose, for example, that, at a particular time in the emergency the exposure without protection is 10 $mg/m^3$, and the probability of completing a protective action is 0.2 or two people completing for every eight that have not completed the action. Further suppose that the action under consideration completely avoids exposure—protection capacity equals zero. The expected exposure is 0.8 times ten, or 8 $mg/m^3$ during that period; however if there were ten people in the area during that period, none of them received an 8 $mg/m^3$ exposure. In fact, two received no exposure at all, while eight were exposed to 10 $mg/m^3$.

## 1.5 OVERVIEW

In meeting the conceptual objectives of developing a method for evaluating protective action alternatives, this report is characterized by two central thrusts: the model development and the preliminary analysis using the model. The development of the evaluation model involves two aspects: (1) the analysis of existing data and research required to determine the relevant input for the model and (2) the actual development of the model accomplished by specifying the relationships among relevant elements. The preliminary analysis has two central purposes: (a) to validate the model and (b) to provide initial insight concerning protective action effectiveness to eliminate further consideration of protective action alternatives that are not viable. These twin purposes are evidenced throughout this report.

Section 2 discusses the general framework for evaluating protective actions. It begins by presenting a brief description of each protective action being considered, describes the principal distinguishing characteristics of each, and presents the findings of a Delphi Panel assembled to evaluate the actions in terms of their potential utility. The description of each alternative establishes the scope of evaluation in terms of what protective actions will be considered and thereby sets the foundation for the development of the evaluation model. The findings of the Delphi Panel represent qualitative judgments concerning specific alternative implementation of protective actions for chemical hazard. These qualitative findings serve as an initial analysis that both gives preliminary analysis of available alternatives and provides a validity baseline for comparison of the model's results.

Section 3 describes the critical elements of the evaluation of protective actions for various accident scenarios. This involves a detailed description of the accident and emergency response characterization and the characterization of the principal environmental elements. Section 3 is primarily focused on model development in terms of determining relevant elements of the evaluation system.

Section 4 presents the data and methods employed in the current research. First, it describes the distribution of accident scenarios for the purpose of evaluating protective actions in terms of agent type, downwind proximity, and meteorological conditions at the time of each potential accident and then presents the simplifying assumptions for other accident scenario characteristics such as time of day, warning systems, decision making, and toxicological end points. This section discusses the nature of scenario selection so that

the preliminary analyses can be understood in terms of the realistic portrayal of potential accidents and state-of-the-art emergency response scenarios. Second, it presents the representation of the effectiveness of protective actions. This includes the description of the model developed for this research to evaluate the effectiveness of various protective actions and the underlying principles used in developing the Protective Action Evaluator for Chemical Emergencies (PAECE). Finally, Sect. 4 presents the application of these methods in terms of the uncertainty involved, the interpretation of results, and the comparison of results. This section focuses on model development by specifying the relationship between elements of the model.

Sections 5, 6, and 7 describe the analysis and findings for three basic categories of actions taken to reduce exposure through emergency response, evacuation (Sect. 5), in-place shelter (Sect. 6), and respiratory protection (Sect. 7). These sections begin by considering the constraints associated with each class of protective actions, which is primarily model development, and end with analysis and findings which comprise the preliminary analysis. Section 8 compares the results of the analysis presented for evacuation, in-place sheltering, and respiratory protection to develop a generic protection strategy. This integration of results will compare findings across protective action categories to determine an optimum protection strategy. Section 8 also addresses the possibility of combinations of protective actions for some population segments and summarizes the principal conclusions and recommendations resulting from protective action evaluation. Section 8 concludes with implications of the preliminary analysis for emergency planning; hence, this section focuses primarily on analysis in the form of insight concerning effectiveness of protective action alternatives.

# 2. FRAMEWORK FOR EVALUATING PROTECTIVE ACTION

This section discusses the general framework for evaluating protective actions. It beings by presenting a brief description of each protective action being considered and continues with the presentation of the findings of a Delphi panel convened to evaluate the utility of potential protective measures. As such, this section serves as a preliminary analysis on which to base the model development. It also serves as a baseline analysis for comparison of model results.

## 2.1 CATEGORIES OF PROTECTIVE ACTIONS

Six principal categories of protective actions are considered: (a) evacuation, (b) in-place protection, (c) respiratory protection, (d) protective clothing, (e) prophylactic drugs, and (f) antidotes. The various options within each category are listed below. Appendix C discusses each category in more detail and in terms of its principal advantages and disadvantages.

### 2.1.1 Evacuation

Evacuation involves changing location to avoid exposure, which includes moving by foot or vehicle to an area outside the exposed areas. There are essentially two kinds of evacuations: precautionary and reactive. A precautionary evacuation requires people to move before the release of a hazardous material, and reactive evacuations move people after a chemical release occurs.

### 2.1.2 In-Place Protection

In-place sheltering involves taking refuge in various kinds of structures. Five types of sheltering have been identified to be of interest for protection from chemical agents.

- Normal sheltering consists of taking refuge in existing, unmodified buildings.
- In expedient sheltering, people take refuge in existing structures that are modified at the time of an accident to reduce infiltration by using common resources and materials, such as plastic bags, tape, and wet towels.
- Enhanced sheltering involves taking refuge in structures in which infiltration has been reduced via weatherization techniques before the occurrence of accidents.
- Specialized sheltering consists of commercial tents or structures explicitly designed for protection in chemical environments.
- In pressurized sheltering people take refuge in existing or specially constructed structures that are pressurized to replace infiltration of toxic vapors with the infiltration of filtered air.

### 2.1.3 Respiratory Protection

Respiratory protection provides noncontaminated air for inhalation in potentially contaminated environments. This involves either (1) the use of protective devices that remove airborne chemicals, aerosols, and vapors from the air prior to inhalation or (2) the direct inhalation of noncontaminated air. Seven types of respiratory protection have been identified as being of interest in providing protection from chemical agents:

- Gas masks with filters or filtering materials to remove airborne toxic compounds inhalation.
- Hoods with fan-driven filters to be placed over the head and sealed at the waist and wrists to remove contamination from the air before inhalation.
- "Bubbles" are sealable containers equipped with a fan-driven filter that surround an individual with a protected environment. They are typically used for protection of infants and toddlers.
- Mouthpiece respirators are small tubes connected to filters and designed to be inserted into the mouth. Users are instructed to breathe through the mouth and tube, thereby filtering the air.
- Use of the facelet mask involves covering the nose and mouth with a charcoal filter cloth expressly designed for use in respiratory protection from toxic chemicals.
- Expedient respiratory protection involves placing a wet cloth over the nose and mouth to remove contamination before inhalation.
- Self-contained breathing apparatus (SCBA) provides noncontaminated air supplied by tanks for inhalation. The tanks normally are portable, although they could be prepositioned at strategic locations.

### 2.1.4 Protective Clothing, Prophylactic Drugs, and Antidotes

Protective clothing employs a whole-body covering to avoid the deposition of chemicals on the skin. Two types of protective clothing are of potential interest for protection from chemical agent.

- Special protective clothing designed expressly for protection from skin deposition.
- Expedient protective clothing, which involves using available clothing to protect from skin deposition.

This analysis does not address skin deposition as an issue of central importance. The public is not likely to come in contact with liquid agent but may encounter agent in vapor form. Appendix A discusses in greater detail issues relating to the public's use of protective clothing.

Prophylactic drugs are used before agent exposure for the prevention or mitigation of agent effects. This protective action has been seriously considered only for potential nerve agent exposure.

Antidotes are used to relieve, prevent, or otherwise counteract adverse effects resulting from agent exposure. Antidotes are somewhat agent specific in that nerve agents (as a group) and vesicants require different antidotes.

## 2.2 THE DELPHI WORKSHOP

### 2.2.1 Workshop Objectives

In an effort to quantify the degree of protection provided by the individual and in-place actions described in Sect. 2.1.2 and 2.1.3 above, each action was further examined to determine its mode (reduces exposure, extends time period user can be away from shelter, etc.) and limitations (requires electricity or batteries?, extensive training necessary?, etc.). This task was accomplished by convening a panel of specialists with expertise in the areas of military medicine, atmospheric chemistry, hazard warning systems, disaster planning, and behavioral science to evaluate the degree of hazard reduction each action could provide (see Table 2.1). Two panelists (Birenzvige and Sidell) possessed specialized knowledge of the chemical agents in question (see Table 1.1). During a weekend in February 1989, the panelists, conveners, and resource staff employed a "Delphi" process to rank all options after considering the safety, system requirements, and intrusion characteristics inherent to each (Starling 1979).

The overall objective of this exercise was to identify the maximum protection consistent with public acceptance. This was accomplished by

- identifying the feasible array of protective actions;
- qualitatively estimating the protection provided by each;
- identifying the advantages/disadvantages of each;
- considering the sensitivity of each protective action to available time, training, maintenance, and other pertinent constraints; and
- evaluating the overall protection provided by combinations of protective actions (i.e., face masks while evacuating).

The panelists agreed that 100% protection from all agents under all conditions was not attainable. However, they also agreed that near-100% protection would be provided by military-issue Level A toxicological agent protective (TAP) clothing [protective suit, hood, respirator, gloves and boots (see Appendix A)] or pressurized mass shelters supplied with charcoal-filtered air under circumstances when affected populations could be expected to be in these shelters before hazard onset. These particular actions were considered reference points for comparison.

### 2.2.2 Workshop Findings

Group discussion classified parameters of interest under the broad criteria of safety (protection during implementation, protection once in place, implementation speed, secondary contamination), system requirements (amount of training, all-clear required, resources required, electricity required, maintenance, and skill/use) and intrusion (initial

**Table 2.1. Participants in protective action Delphi Workshop held February 16-18, 1989, in Oak Ridge, Tennessee**

**Conveners**

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Energy Division
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Annetta Watson
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Conrad V. Chester
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Robert Miller
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**Panelists**

Amnon Birenzvige
U.S. Army Chemical Research
Development Engineering Center
Aberdeen Proving Ground, Maryland

Michael Lindell
Department of Psychology
Michigan State University
Ann Arbor, Michigan

Dennis Mileti, Director
Hazards Assessment Laboratory
Colorado State University
Ft. Collins, Colorado

Frederick Sidell, M.D.
POT Branch
U.S. Army Medical Research
Institute of Chemical Defense
Aberdeen Proving Ground, Maryland

and ongoing). The various in-place shelter options (normal, specialized, expedient, pressurized, and enhanced) and individual respiratory protections (gas mask, hood, baby "bubbles," mouthpiece respirators, facelet mask, expedient, and SCBA) defined in Sect. 2.1 were ranked by the Delphi Group from least desirable (1) to most desirable (5) based on how well they achieved the elements of safety, system requirements, and intrusion. For estimating rank values, each participant was asked to evaluate both the physical ability of specific protective actions to reduce exposure and the behavior required to implement the given protective action. Individual rank values were averaged for the group and are depicted in Figs. 2.1 and 2.2. For the purpose of the analysis, the only evacuation type considered was "responsive." The panel found that *responsive evacuation* can quite effectively reduce exposure only when it can be completed before onset of the plume. Thus, responsive evacuation would be the most appropriate protection alternative for people in areas far enough away from the source to provide time to complete the implementation of an evacuation, but would be unlikely to protect people in areas in close proximity to the source under conditions that fail to provide adequate response time. In a similar vein, precautionary evacuation is always desirable, always effective, and provides near perfect protection. The panel generally recommended that *precautionary evacuation* would be advisable if sufficient advance warning and adequate implementation time before a potential release are available. However, the occurrence of an unplanned release, particularly if the incident is fast breaking, precludes consideration of precautionary evacuation.

All the criteria considered by the panel do not carry the same weight. Safety aspects are far more important than, say, intrusiveness, during consideration of the best protective action to recommend for a given chemical agent emergency. A good example would be normal sheltering, where use of an existing unmodified building (usually a dwelling) would not be intrusive and no additional training, resources, electricity, maintenance or skill would be required for implementation (Fig. 2.1). However, the degree of protection provided by normal sheltering is minimal and is further compromised by the high probability of secondary contamination (Fig. 2.1). Because of the small degree of safety inherent to the normal sheltering option, the panel would not recommend it for anyone. Other sheltering options provide more protection, although they are more intrusive and subject to greater system requirements, would be recommended instead. In descending order of safety, the shelter options were ranked by the Delphi Panel as follows: pressurized shelters provide the greatest safety, followed in order by enhanced, specialized, expedient, and normal shelters. Enhanced shelters are considered safer than specialized shelters because of the minimal protection offered while traveling to the specialized unit and the greater time required to implement the protection provided by the specialized shelter. The reduced infiltration characteristics of enhanced shelter are assumed to be in place before the agent plume reaches the shelter's location.

A similar classification can also be performed for the system requirements of in-place shelter options; normal sheltering requires very little, while enhanced shelters require prior weatherization procedures to reduce infiltration. System requirements during the response are such that expedient and pressurized shelters each require more than normal and enhanced shelters; specialized shelters have the most system requirements during implementation and upon initialization. In-place shelter options also can be ranked

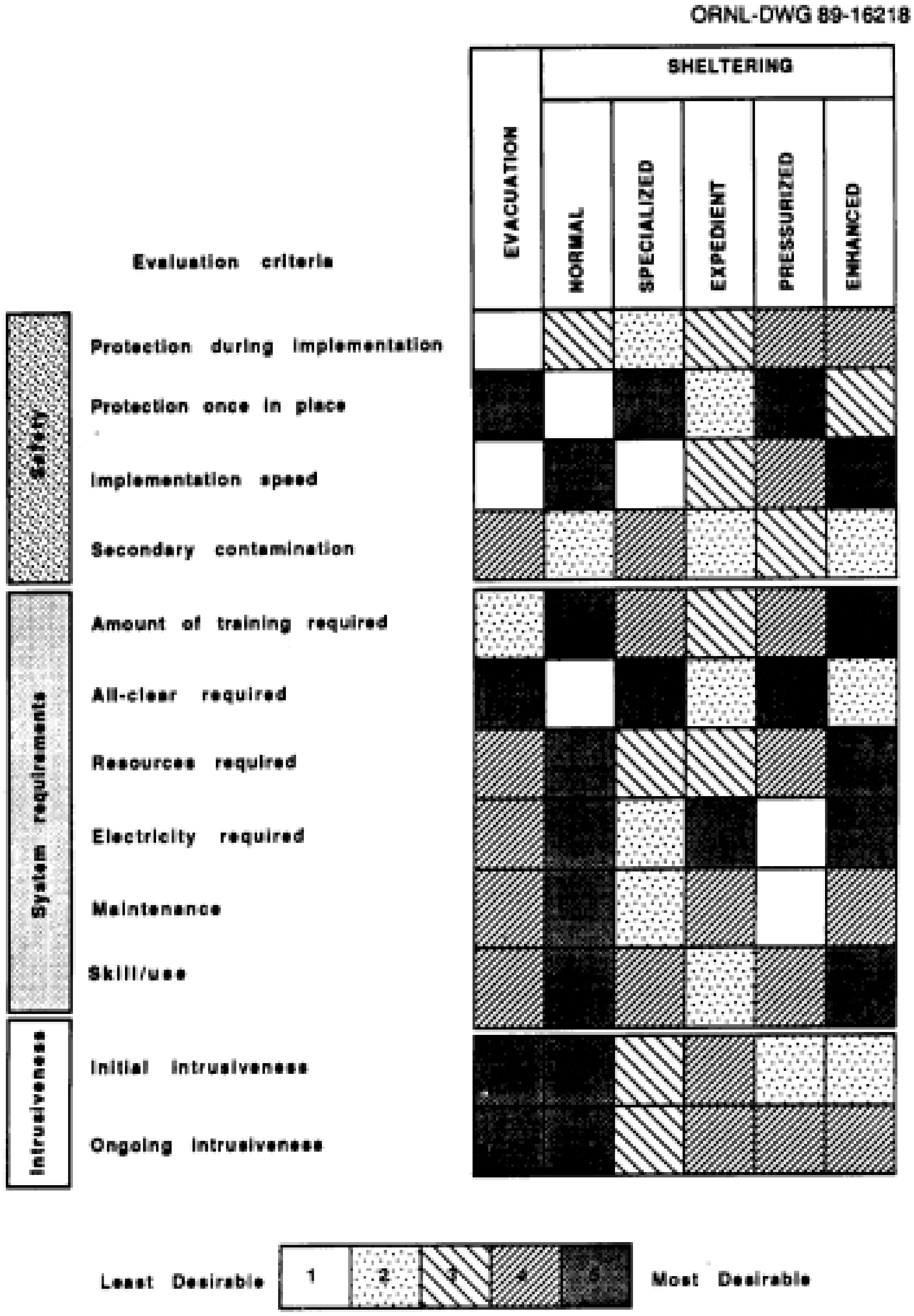


Fig. 2.1. Expert panel evaluation of evacuation and sheltering.

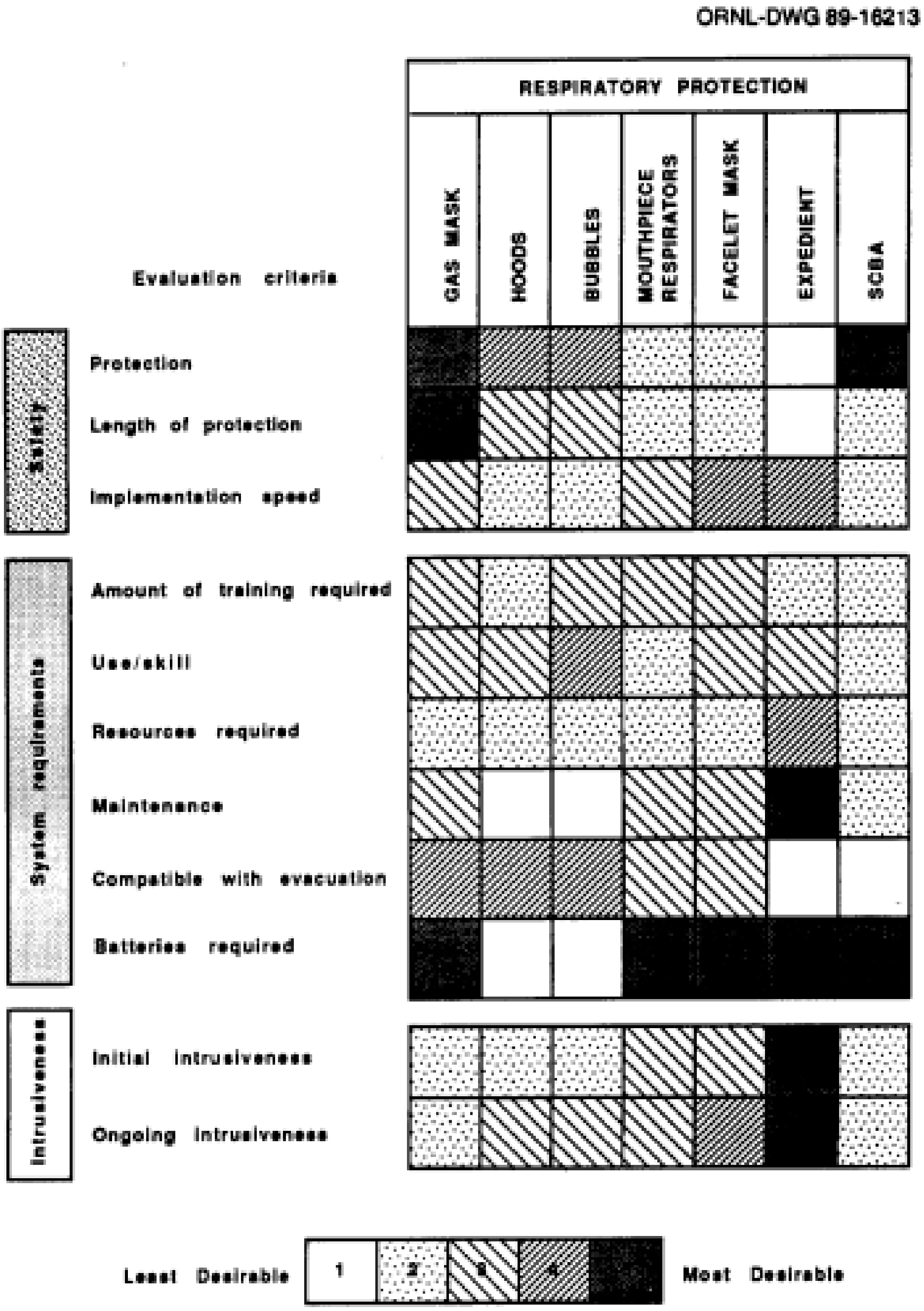


Fig. 2.2. Expert panel evaluation of respiratory protection options.

regarding their intrusiveness; because nothing needs to be done for the normal shelter option in advance, it is the least intrusive. Expedient shelters require little preparation, and accessing routinely available household items would not be intrusive. Enhanced, pressurized, and specialized shelters all require some installation of system elements, with pressurized and specialized shelters being the most intrusive.

Overall, pressurized shelters provide the greatest safety with modest system requirements and limited ongoing intrusion. Hence, the panel found that *pressurized shelters* offer the best overall in-place protection available and are particularly suitable for institutionalized populations that would find it difficult to evacuate in a timely manner (e.g., hospitals, nursing homes, and nearby schools) and that have patient populations located inside at the time of an accident. Enhanced shelters that reduce infiltration via recognized weatherization techniques can provide considerable protection with acceptable system requirements and limited intrusion. The panel found that *enhanced shelters* provide very good protection, primarily because of their rapid implementation but in part because of the potential, with their use, to combine enhanced protection with expedient measures within the weatherized structure. While normal sheltering is characterized by very limited intrusiveness, it provides quite limited protection, particularly for older homes thought to be characterized by high infiltration rates. Hence, *normal shelters* are not recommended for areas likely to be exposed to lethal concentrations of agent. Normal shelters might provide limited protection from nonlethal concentrations or could be combined with expedient sheltering to provide more appropriate protection.

Various types of respiratory protection were ranked in the same manner as in-place shelters (Fig. 2.2). Respiratory protection reduces the adverse effects of vapor exposure, which is the principal concern with the volatile agents GB and GA. Vapor is considered the most likely form of release that could affect an off-post population (U.S. Department of the Army 1988). Because vapors are not readily absorbed through the skin, the donning of extra layers of clothing in addition to a mask or respirator will provide little or no additional protection.

Of the respiratory protection options considered, summary rankings in the three basic categories of safety, system requirements, and intrusiveness are given below in descending order of desirability. The panel found that masks provide the highest degree of safety with limited system requirements, although they were deemed intrusive, when compared with other respiratory protection alternatives. Expedient respiratory measures provide the least amount of protection but have limited system requirements and very limited intrusiveness. While hoods, bubbles, and SCBA meet safety requirements, they were considered to be fairly intrusive and have high system requirements. The mouthpiece respirator and facelet mask provide more limited protection but have lower system requirements and intrusiveness. The panel found that despite the fairly high intrusiveness, *masks* provide the best overall respiratory protection for people in close proximity to the potential source of release, particularly when used in conjunction with other measures of protection (e.g., evacuation or in-place sheltering). Even though the panel recognized the more limited protection offered, they found that the *facelet mask* and the mouthpiece respirator provide considerable protection for people in close proximity, when used in conjunction with evacuation. Even though they are characterized by extremely low intrusiveness, *expedient respiratory* measures are not recommended, because they offer

extremely limited protection. In addition, such a recommendation would undermine the credibility of the emergency preparedness program.

In the event of liquid agent splash or aerosol release (the principal exposure pathway of concern for the persistent agent VX and the mustards), respiratory protection can provide only partial protection. The physical properties of liquid VX or mustard will confine most liquid contamination within close proximity to the source, which, in the majority of cases, will be within the boundaries of the installation. Use of military-design clothing will be the recommended protective action for individuals who may come in close contact with liquid agent. The use of protective clothing to reduce exposure to persistent agent liquid and/or aerosols is discussed more fully in Appendix A.

# 3. PROTECTIVE ACTION EFFECTIVENESS

The dynamics of the discussion among the Delphi Panel underscored a fundamental debate between those who focus their attention on the ability of the device or action to protect and those who emphasize the behavior required to implement a protective action. These opposing points of view either focus on the individual protective measure or put the protective measure in the entire system of response required to make the action effective. Hence, the approach taken herein separates the physical ability of protective actions to protect from the response required for that action to be taken. Effectiveness may then be examined in terms of the response-adjusted exposure reductions. This approach evaluates the effectiveness of protective measures in the context of the complete emergency response system and the emergency planning required to achieve protection.

This section describes critical elements of the evaluation of protective actions. This section partitions these elements into three groups regarding (1) the accident and its consequences, (2) the emergency response to the accident, and (3) the environment. First, however, it discusses the approach used in the development of the evaluation method. This section is focused primarily on model development, addressing the critical elements of the evaluation model.

## 3.1 EVALUATING PROTECTIVE ACTIONS

Conceptually, the effectiveness of any particular action taken to protect people in the event of a chemical accident depends on the ability of the action to reduce chemical exposure to tolerable levels and the probability that the people to be protected take the action in a timely manner. Two factors that determine the ability of an action to reduce exposure to tolerable levels are the degree of hazard or amount of toxic agent present in the unprotected environment and the action's ability to either reduce or avoid that exposure. The timeliness may be thought of as a function of the amount of time it takes for a toxic plume to travel to a given distance, compared with the time it takes the emergency response system to get people at that distance to take the action.

Evaluating the effectiveness of protective actions rests not only on the ability of a selected action to reduce or eliminate exposure but also on the emergency response system required to implement that protective action. Recall that Fig. 1.2 presents the conceptual framework for evaluating protective action effectiveness employed in this report. The emergency is characterized in terms of the accident, the dispersion of the resulting release, and the human health consequences associated with the resulting exposures. The response to the emergency is summarized in terms of the probability that the selected protective action will be implemented at a particular time. Expected exposure is represented in terms of (1) the exposure that would be expected without protection, (2) the exposure given the probability that the selected protective action is implemented, and (3) the exposure given that the protective action is unconstrained by behavior (i.e., operating at its protection capacity). These expected exposure estimates are then compared with each other and the expected human health consequences associated with exposure at that level.

This method uses protection factors to establish the protection capacity of the protective actions for the specific release being considered and employs the previous disaster research in the determination of the probability of implementing a specific protective action. This approach is probabilistic in that estimates of expected exposure are based on the probability of completing the protective action which depends on the entire emergency response system, which has the advantage of representing expected exposure for the population at risk. However, it has the disadvantage of not representing the exposure of any particular individual at all. Hence, the expected exposure is the unprotected exposure times the probability of not completing the protective action, plus the probability of completing the action times the protected exposure.

### 3.1.1 Principles of Development

Protective actions need to be examined in the context of potential accidents, the complete emergency response system, and the environment that effects each. This research develops a model of emergency response effectiveness that characterizes (1) potential accidents as they are likely to occur, (2) the complete emergency response system that leads to the implementation of the protective action, and (3) those parts of the environment that significantly effect either the character of the accident or the nature of the response, or both. This approach puts the evaluation of the effectiveness of each protective action in the context of the identified potential for harm and the comprehensive emergency response system.

Two basic considerations underlie the effectiveness of each protective action. First, the inherent ability of each measure to avoid or reduce exposure. Hence, the capacity to protect or avoid includes only the physical ability of the action to protect or avoid. For example, the ability of a respiratory device to protect is dependent upon (1) the efficiency of the charcoal filter in removing airborne chemicals and (2) the degree to which leakage around the filters can be prevented. This physical capacity of the protective action to provide protection determines the maximum exposure reduction that people using it can achieve.

The second consideration is the amount of time a given action requires to be completed, because a protective measure can reduce exposure only when it is implemented. The completion of a protective action involves the time it takes (1) to detect the hazard, assess the situation, and decide that a warning is appropriate; (2) to disseminate the warning message that both alerts people to the potential for harm and notifies them concerning appropriate responses; (3) for the public to decide on an appropriate course of action; and (4) for people to implement the selected action. This timing determines the extent of exposure before implementation of the protective action.

In the process of developing a system to evaluate the effectiveness of protective actions, several guiding principles were used.

• *Flexibility* To be useful, any system of evaluation must be flexible enough to accommodate the potential situations to be evaluated. Flexibility is particularly important when evaluating emergency response systems, because (1) accidents seldom occur as expected, (2) emergency responses are usually dynamic processes that adjust to changing situations, and (3) protective action decisions are influenced by local conditions. To

evaluate the effectiveness of various protective actions, the system has to be flexible enough to accommodate these dynamics to meet the response objective.

• *Empirically based* To be useful any system of evaluation must be based on reality; one way to obtain this reality is to build in data, conclusions, and knowledge from existing research. The system accommodates, and builds on, existing knowledge of emergency response and the protective capacities associated with various protective measures to realistically portray effectiveness; hence, empirical evidence is used wherever possible to validate any assumptions employed. Starting from such an empirical base allows the evaluator to examine hypothetical changes in the system in the context of existing knowledge. Some systems may be effective only when elements of the system are altered, improved, or modified.

• *Parsimony* Any system of evaluation is a representation of the complete process; such systems focus on the main elements of the situation (i.e., those parts of the system that fundamentally alter the outcomes). Because accidents and associated emergency responses are quite complex events, the evaluation system must focus on critical components of the process; a parsimonious solution is preferred to the extent that it depicts the critical elements of the situation.

• *Modular development* Any system of evaluation must be able to accommodate changing information, knowledge, and methodologies over a period of time. Modular development allows critical elements to be extracted from the system and replaced with new components as long as the inputs and outputs from the new elements are similar. Because new information and approaches are being developed continuously, the evaluation system should be modular to accommodate improved understanding of either the character emergency response systems or accident trajectories.

• *Uncertainty and precision* The precision of an evaluation resulting from a system should be commensurate with the amount of uncertainty in the system and its components. Because uncertainties exist throughout the system of evaluation and characterize every component, qualitative interpretation of graphic results is preferred to quantitative numeric results. Presentation of precise numeric information is avoided to accommodate the associated uncertainty.

The remaining sections of this chapter examine the relevant aspects of chemical accidents, emergency response, and the operating environment. Section 3.2 considers the pivotal characteristics of chemical accidents resulting in a vapor plume exposure pathway. Section 3.3 discusses the characterization of the relevant aspects of emergency response, and Sect. 3.4 identifies the significant characteristics of the environment in which a chemical accident might occur.

## 3.2 CHARACTERIZING THE ACCIDENT

An accident involves the occurrence of an event that leads to the release of chemicals as they are distributed from a source point. Section 3.2.1 discusses the stochastic representation of when chemical accidents have occurred. Section 3.2.2 summarizes the distribution of accidents believed to be credible. Section 3.2.3 discusses the plume dispersion model used in the current analysis that characterizes the plume

exposure pathway. Section 3.2.4 summarizes the state of knowledge concerning the distribution of human health consequences of agent exposure.

### 3.2.1 Time of Accident

Chemical accidents occur with temporal and spatial dimensions; because the focus of this report is on the effectiveness of protective actions for fixed locations, the spatial dimension of the accident problem is known. Temporally, an accident can occur any time of day on any day of the week. While chemical accidents can occur at any time, the probability of occurrence can be significantly impacted by operating schedules and procedures and system maintenance. Because the systems that produce, store, transport, use and destroy chemical agents are human systems, the actual distribution of accidents is related inherently to social, organizational, and behavioral processes and thereby is unlikely to be uniform. Figure 3.1 presents the distribution of chemical accidents involving public evacuations reported by the Associated Press (AP) and United Press International (UPI) between January 1985 and September 1988.

These data are not directly relevant because they summarize military and commercial accidents involving toxic chemicals, and it is unclear the degree to which the operation of the CSDP facilities conforms to the "typical" schedule underlying this distribution. Nonetheless, these data do indicate the general relationship between behavioral/operational schedules and time of accident. These data indicate that the most probable hour of the day for a chemical accident is between 10 and 11 a.m.; accident frequency increases before that hour, starting around 9 a.m. and declines after 11 a.m. Overall, the peak accident period runs from around 9 a.m. to 1 p.m. These data indicate that accidents in the peak hour of 10 to 11 a.m. occur with a frequency that is more than twice what would be expected given a uniform distribution. Examining only fixed-facility accidents in the database portrays a similar pattern, with fixed-facility accidents accounting for more than half the accidents in any given hour except the noon hour, where transport accidents are more prominent. While the remaining portions of the distribution for fixed-facility accidents are relatively uniform, several minor peaks are detectable (i.e., 6 a.m., 3–4 p.m., 6–7 p.m., and 11 p.m.).

The emergency planning implication of these data for chemical accidents is that no period of the day or night can be neglected. Moreover, the consideration of protective actions required to reduce potential exposures must encompass the possibility of an accident at any hour of the day. Operating schedules and procedures may be used to alter or mitigate the circumstances that lead to the distribution and thereby alter the distribution of probabilities of an accident by hour of the day. The probabilistic selection methods simply choose the hour of the accident based on the hour where most accidents occur (most probable), a random selection with probabilities equal to the actual distribution as represented in Fig. 3.1 (stochastic), or a random selection with equal probabilities for each hour (1/24). In addition, the user can also select the hour and minute of occurrence directly.

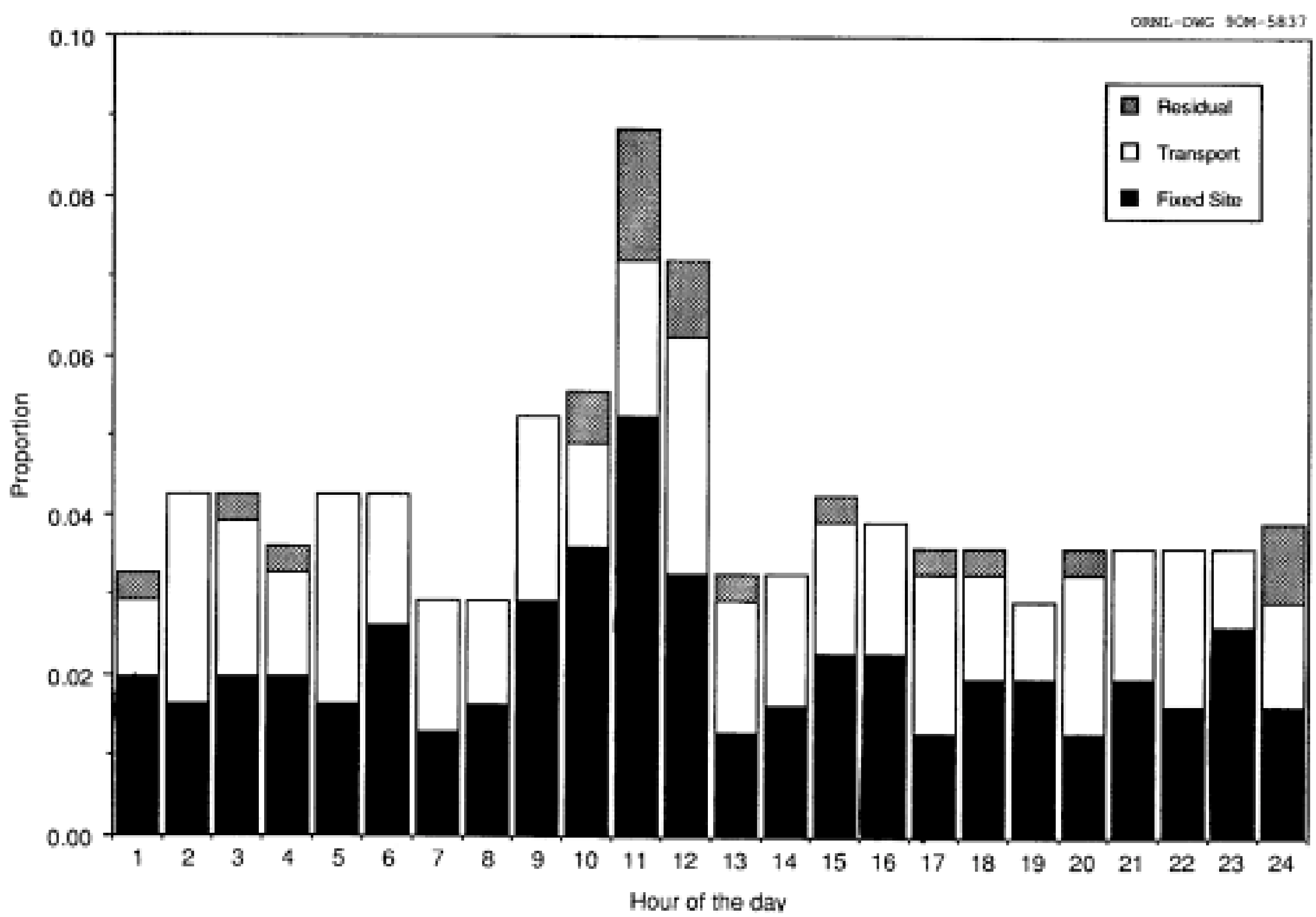


**Fig. 3.1.** Distribution of chemical accidents involving public evacuations by hour of the day. Data for graph from Associated Press and United Press International Reports—1985 to September 1988.

### 3.2.2 Characteristics of Potential Accidents

The distribution of potential accidents at sites currently storing the unitary chemical stockpile was studied in the course of the preparation of the programmatic environmental impact statement for the CSDP (U.S. Army 1988). The results of that analysis played a critical role in the decision for on-site disposal (Ambrose 1988). While it is impossible to know in advance all the possible accidents that could occur at the sites currently storing the unitary chemical stockpile, this analysis represents the distribution of accidents with the information contained in the database developed for the program (Fraize et al. 1987), which represent accidents considered credible because they have at least a $1 \times 10^{-8}$ probability of occurrence (at least 1 chance in 100 million).

Because the munitions and containers (except the M55 rockets) are part of a strategic stockpile, the size of the stockpile is classified. Moreover, the accident probabilities cannot be divulged because they are partly based on inventory size. Because emergency planning decisions, historically, have been relatively insensitive to the probability of credible accidents having classified accident probabilities presents only minor problems for emergency planning purposes, the underlying philosophy being that, if an accident can occur, emergency preparedness should be ready to mitigate the consequences. However, as emergency managers are faced with fiscal constraints, critical decisions require that emphasis be placed on more likely emergency events.

One way to accomplish this represents the distribution of accident characteristics in terms of the middle of the distribution. This approach compares accident scenarios to a baseline established as the middle of the distribution. Another way represents the distribution of credible accidents in terms of a class of accidents that are similar. Because protective actions for chemical emergencies attempt to mitigate the consequences of potential accidents, the selection of credible accidents is more sensitive to characteristics effecting potential consequences than the estimated probability of occurrence. Among a group of accidents with similar consequences, emergency planning for a low- or high- probability event serves to mitigate the consequences for all accidents in that group, regardless of probability. The evaluator can determine how extreme the event is by comparing the specific accident scenario, or class of accidents to the typical accident characteristics.

Table 3.1 summarizes the distribution of credible accidents, by site and agent type, in terms of average amount of agent released, estimated downwind distance under two meteorological conditions, and duration of release. While these averages represent the center of the distribution, more extreme accidents lead to greater consequences. Five of the eight storage facilities currently have volatile nerve agents (GB or GA) in their inventory; PUDA and APG store only mustard agents (HD or HT), and NAAP only has VX. Among those sites having GB or GA, the average amount expected to be released is 100 kg, with the highest average being 230 kg at UMDA and the lowest being approximately 30 kg at LBAD and TEAD. These release scenarios are characterized by an average downwind distance of 2 to 6 km, with UMDA being slightly higher at 2 to 9 km and TEAD being a little lower at 1 to 4 km. The average expected release of agent in this category lasts about 1.5 h; the average release time varies between 86 and 122 min at PBA and ANAD respectively.

Table 3.1. Estimated characteristics of accidents by site and agent type

| Site | GB | H/HD | VX |
|---|---|---|---|
| | | Agent type: | |
| | | **Average quantity of agent released (kg)** | |
| ANAD | 140 | 890 | 220 |
| APG | NA | 370 | NA |
| LBAD | 30 | 60 | 20 |
| NAAP | NA | NA | 9800 |
| PBA | 40 | 6040 | 60 |
| PUDA | NA | 2110 | NA |
| TEAD | 30 | 1680 | 350 |
| UMDA | 230 | 72100 | 30 |
| All Sites | 100 | 13400 | 800 |
| | | **Average no-death downwind distance under 3 m/s winds and D stability (km)*** | |
| ANAD | 2 | 1 | 3 |
| APG | NA | 1 | NA |
| LBAD | 2 | 0 | 3 |
| NAAP | NA | NA | 16 |
| PBA | 2 | 3 | 2 |
| PUDA | NA | 2 | NA |
| TEAD | 1 | 1 | 3 |
| UMDA | 2 | 12 | 2 |
| All Sites | 2 | 3 | 3 |
| | | **Average no-death downwind distance under 1 m/s winds & E stability (km)*** | |
| ANAD | 7 | 6 | 11 |
| APG | NA | 4 | NA |
| LBAD | 6 | 2 | 5 |
| NAAP | NA | NA | 91 |
| PBA | 7 | 19 | 9 |
| PUDA | NA | 11 | NA |
| TEAD | 4 | 7 | 16 |
| UMDA | 9 | >100 | 6 |
| All Sites | 6 | 26 | 16 |
| | | **Average duration of accident (min)** | |
| ANAD | 105 | 179 | 110 |
| APG | NA | 109 | NA |
| LBAD | 117 | 133 | 120 |
| NAAP | NA | NA | 164 |
| PBA | 122 | 113 | 127 |
| PUDA | NA | 136 | NA |
| TEAD | 86 | 157 | 145 |
| UMDA | 90 | 211 | 123 |
| All Sites | 96 | 150 | 129 |

*Stability classes are used to represent the extent of atmospheric turbulence at the location at the time of the accident. Several widely used classification schemes are available. The most widely used scheme was originally proposed by Pasquill (1961), for diffusion from low-level, nonbuoyant sources over open country. The categories of stability class are: (A) extremely unstable conditions, (B) moderately unstable conditions, (C) slightly unstable conditions, (D) neutral conditions, (E) slightly stable conditions, (F) moderately stable conditions, and (G) extremely stable conditions. Gifford (1976) examines modifications to Pasquill's scheme to account for elevated and buoyant releases, boundary-layer stability, and diffusion over great distances.

Seven of the eight sites currently have mustard agents (H, HD or HT) stored at the installation; only NAAP does not have mustard. Among those sites having mustard agents, the estimated average amount of agent released is nearly 13,400 kg, with the smallest average release consisting of 60 kg at LBAD and the largest average release being nearly 72,100 kg at UMDA. These releases result in average estimated downwind distances from 3 to 26 km. The largest releases can result in deaths from 12 km to more than 100 km at UMDA, while the smallest releases transcend the installation boundaries only under weather conditions characterized by inversion conditions and reach average downwind distances of 2 to 19 km. The average duration of mustard releases exceeds 1.5 h at every site where mustard is stored. The average duration of release is about 2.5 h, with the largest average duration nearly 4 h at UMDA and the smallest average duration being just under 2 h at APG.

Six of the eight sites currently store persistent nerve agent (VX); all sites store VX except PUDA and APG. Among those sites currently storing VX, the average estimated release is 800 kg, with the largest release of more than 9,800 kg occurring at NAAP and the smallest release of 20 kg occurring at LBAD. These release scenarios result in average no-death downwind distances of between 3 and 16 km, with the largest releases at NAAP resulting in average downwind distances from 16 to 91 km and the smallest average releases at LBAD resulting in average downwind distances between 3 and 5 km. The average expected duration of a VX release is just over 2 h; ANAD has an average duration of release less than 2 h (110 min), while NAAP has the largest average duration at nearly 3 h (164 min).

Although the average characteristics presented here represent the middle of the distribution of potential accidents, they fail to characterize the extreme events. For example, while the average amount of agent type GB released is 100 kg overall or 230 kg at UMDA, the maximum release exceeds 6,000 kg at UMDA, TEAD, and ANAD. In addition, to meet the response objective, the system must be able to characterize any event, even those not specifically included in the database of accidents developed for the FPEIS. Hence, for the purpose of evaluating protective actions, in addition to selecting any given accident or group of accidents characterized in the risk analysis data, virtually any size of release over any conceivable duration can be selected. Because the accident probabilities are classified, no stochastic or most probable selection is permissible.

### 3.2.3 Plume Dispersion

One of the critical elements when considering the effectiveness of various protective actions is the hazard characterization in terms of exposure at various downwind distances. An accurate assessment of the onset, duration, and magnitude of the hazard is a prerequisite for evaluating protective actions. The system of evaluation uses an existing atmospheric dispersion code to evaluate the hazard by estimating the total exposure from a release of chemical agent. The dispersion of agent is determined over time at a given downwind distance from the source of the release. Total exposure is estimated using D2PC, which is an air dispersion model developed by Whitacre et al. (1987) specifically for the determination of exposure to chemical agents. The D2PC model assumes a Gaussian distribution of agent in the vertical and crosswind directions as the agent

disperses downwind. The development of Gaussian models has been documented extensively in the literature (Sutton 1932; Gifford 1968; Pasquill 1974), and many models currently use a Gaussian distribution (U.S. EPA 1986).

The D2PC code, which incorporates the effects of both aerosol and vapor, predicts exposure of agent expected at locations downwind of a release. The greatest advantage of the D2PC code is that detailed information on the type of accident to be modeled is incorporated in the code. Input parameters include type of agent (VX, GB, or mustard); mode of release (explosion, fire, or spill); and duration of the release. This sophisticated characterization of the source term, based upon field tests and detailed analysis by experts in agent characteristics, is one of the strengths of the model. A vapor depletion technique is also included in D2PC to estimate the removal of agent vapor from the atmosphere by deposition on surfaces during transit from the point of release. Due to the ability of the human body to metabolize certain nerve agents, a correction for the length of exposure, termed the "2-min factor," is employed to prevent overestimation of impacts from a very long exposure to very low concentrations. Although more complex dispersion codes are available, the assumption in the D2PC model of straight-line transport with nonvarying meteorological conditions overestimates the effects of releases.

The results of another air dispersion model called PARDOS are incorporated in the evaluation system to estimate the exposure accumulated with time at a given distance (Seigh 1988). The concentration over 1-min intervals is summed to provide the unprotected exposure for a given distance. PARDOS assumes the same Gaussian distribution of agent but does not include some of the more sophisticated techniques in D2PC, such as vapor depletion. Therefore, the results of PARDOS are normalized by the total exposure derived by D2PC so that the shape of the curve representing exposure accumulated with time is the same as calculated by PARDOS, but the total exposure matches the results obtained by D2PC.

Depending on the duration of a release, the models are capable of using either Gaussian plume or puff dispersion equations. The plume equations calculate the total exposure received at a given distance in terms of the concentration of agent along the center-line of the plume as

$$C = Q / [2 \pi u \sigma(y) \sigma(z)] ,$$

where C is the concentration in $mg/m^3$, Q is a continuous source strength or quantity of agent to be dispersed into the atmosphere in mg/s, and u is the average wind speed. The $\sigma(y)$ and $\sigma(z)$ parameters are standard deviations of the plume in the y (horizontal crosswind) and z (vertical) directions (Hanna et al. 1982). The centerline assumption forms an upper bound on the amount of agent a randomly placed individual under the plume is exposed to by assuming that each person is exposed to the maximum concentration along the centerline of the plume.

Conceptually, the cumulative exposure at a given downwind distance is the integration with time of the concentration within the plume. Practically, this is estimated as the summation of concentrations within a series of plume segments that pass the given location. The partial exposure up to time, t, following a release from a semicontinuous

source (a release for a specific duration resulting in a plume) is calculated (Milly 1958) as

$$D(x,y,z,t) = \frac{Q\exp\left[-\left(y^2/2\sigma^2 y\right)\right]\left\{\exp\left[-(z+H)^2/2\sigma^2{}_z\right]+\exp\left[-(z-H)^2/2\sigma^2{}_z\right]\right\}}{4\pi\sigma_y\sigma_z u}$$

$$\bullet\frac{\sigma x\sqrt{2}}{u}\left\{DEF\left(\frac{x-ut}{\sigma_x\sqrt{2}}\right)-DEF\left(\frac{x}{\sigma_x\sqrt{2}}\right)\right\}$$

(if $t \leq t_e$, the ending time of the release).

When $t > t_e$,

where

$$DEF(A) = \int_O^A erf(\lambda)d\lambda$$

and

$$H = H_o + V_o / K\ (1 - e^{-Kx/u}) .$$

are implicit functions in D(x, y, z, t) .

The parameters in the equations are defined as follows: Q is the rate of release in mg/sec; u is the average wind speed in m/sec; x is the downwind distance in m; y is the crosswind distance from center line of plume in m; z is the sample height in m; $t_e$ is the ending time of release in seconds; H is the height of center of plume in m; $-_x$, $-_y$, $-_z$ are the standard deviations in each direction in diffusion parameters of m as before; $H_o$ is the initial height of source; $V_o$ is the initial velocity of release of agent; and K is the rate constant in $s^{-1}$.

A puff is represented as a centroid located as a direct function of the average wind speed and time. Dispersion ahead and behind the centroid is estimated as a function of fluctuations in wind speed from the mean. Crosswind and vertical dispersion are accounted for by fluctuations in wind direction and change of temperature with height, respectively.

Conceptually, the total exposure at a given downwind distance is the integration of the concentration with time as the puff moves downwind. Practically, this is estimated as the summation of concentrations for discrete time intervals. Along the centerline, the concentration C is generally calculated as

$$C = Q/[(2\ \pi)^{3/2}\ \sigma^3] ,$$

where $\sigma^3$ is the standard deviation of the material in the puff (Hanna et al. 1982). The partial exposure up to time, t, following a release from an instantaneous source is calculated as

$$D(x,y,z,t) = \frac{2Q}{(2\pi)^{3/2}\sigma_x(x)\sigma_y(y)}$$

$$\int_O^t \exp\left\{-1/2\left[(x-ut)^2/\sigma^2{}_x(x) + y^2/\sigma^2{}_y(y) + z^2/\sigma^2{}_z(z)\right]\right\}dt$$

where $\sigma(x)$s are substituted for $\sigma(t)$s (Milly 1958).

While the dispersion code for D2PC represents the atmospheric dispersion quite well in terms of both vapor and aerosol, the PARDOS code represents only the vapor portion of the release for any given agent. Even though the total ending exposure (as based on D2PC) accounts for aerosol depletion, PARDOS does not account for the nature of aerosol dispersion in its partitioning of the exposure for a given downwind distance by time into the event. As a result, the partial exposure results of the dispersion codes employed herein accurately represent the vapor portion of the release. Hence, to the extent that a release of agent is appropriately characterized as vapor the approach to dispersion modeling employed herein is reasonably accurate. Because GB is quite volatile [$2.2 \times 10^4$ mg/m$^3$ at 25°C (U.S. Department of the Army 1974)], and thereby results in a vapor plume, the atmospheric transport of GB is characterized reasonably well. However, because VX releases have significant portions of the release appropriately characterized as aerosol, with lower volatility [10.5 mg/m$^3$ at 25°C (U.S. Department of the Army 1974)] it is less likely to be transported over long distances. Mustard is also characterized by reasonably low volatility [925 mg/m$^3$ at 25°C (U.S. Department of the Army 1974)] and is not likely to be transported for long distances as a vapor. The approach used herein considers the entire release, regardless of agent, to be vapor, and thereby overestimates the amount of agent present at any downwind distance at any moment into the release. This overestimate of the amount of agent concentration is considered conservative because it overestimates the exposure to be protected from and systematically underestimates the ability of each protective actions to protect. Hence, the model most accurately represents the dispersion of GB; it underestimates the level of concentration of VX and H/HD early in the time period at relatively short distances. However, because aerosol droplets are likely to drop out quite quickly (i.e., probably within 0.5 to 1 km), the exposures are likely to be overestimated by the model at distances greater than 1 km.

### 3.2.4 Human Health Consequences

Data quantifying known acute toxic levels (human; estimated) of nerve and vesicant agents are documented in Appendix B of the FPEIS (U.S. Department of the Army 1988) in Tables B.2 and B.13. In most cases, these values were extrapolated from laboratory

animal data to estimate the response of military personnel under conditions of chemical warfare combat. Thus, the tables provide information specific to young adult, male, combat personnel.

Making standard anatomical assumptions regarding body weight, respiratory volume, and surface area (see Table 3.2), the body burden resulting from exposure to a given Ct (atmospheric concentration, C, multiplied by time, t) may be calculated. By further assuming that the body burden derived from the Ct values associated with a specific toxic end point will generate the same toxic end point in individuals with characteristically different anatomical parameters (e.g., adult females, children, and newborns), a new but biologically equivalent Ct can be calculated. This logic assumes that other gender and/or age classes are not inherently more sensitive to nerve or vesicant agent exposure than young adult males. This latter assumption is likely to be untrue due to the thin epidermis, small respiratory passages, and underdeveloped detoxification systems of young children. However, in the absence of age-specific exposure-response data to support scaling on the basis of epidermal thickness, airway diameter or metabolism, a body burden estimated from standard anatomical data is a reasonable approach. For example,

$$B = (Ct)\,(V)\,(1/M)\ ,$$

where B = body burden (mg/kg),
C = agent concentration in air (mg/m$^3$),
t = time (min),
V = minute volume (m$^3$/day),
M = body mass (kg),

then

$$Ct = B/[V(1/M)]\ .$$

From data in Table 3.2, males (light activity) exposed to an $LCt_{50}$ of GB (70 mg-min/m$^3$) will experience a body burden of

$$B = \left(70mg - \min/m^3\right)\left(\frac{28.8m^3}{day}\right)\left(\frac{1day}{1440\min}\right)\left(\frac{1}{70kg}\right)$$

$$= 2.0 \text{ x } 10^{-2}$$

Again using data from Table 3.2, it is possible to calculate the Ct necessary to attain the same body burden in a newborn:

$$Ct = \frac{2.0 \times 10^{-2} mg/kg}{\left(\frac{2.2m^3}{day}\right)\left(\frac{21}{2.5kg}\right)\left(\frac{1day}{1440\min}\right)}$$

$$= 32.7 \text{ mg-min/m}^3$$

**Table 3.2. Major anatomical assumptions used in estimating agent exposure effects for women, children, and infants**

| | Body weight (kg) | Respiratory volume resting L/min ($m^3$/day) | Respiratory volume light activity L/min ($m^3$/day) | Body surface area ($m^2$) |
|---|---|---|---|---|
| Adult Male | 70.0[a,b] | 7.5[c] (10.8) | 20.0[c] (28.8) | 1.8[a,b] |
| Adult Female | 60.3[c] | 6.0[c] (8.6) | 19.0[c] (27.4) | 1.6[b,c] |
| Child (10 years) | 34.5[c] | 4.8[c] (6.9) | 13.0[c] (18.7) | 0.96[c] |
| Newborn | 2.5[c] | 0.5[c] (0.72) | 1.5[c] (2.2) | 0.22[b,c] |

[a]Spector, W. S. (ed.) 1956, Handbook of Biological Data, Tables 146 and 150.
[b]U.S. Department of Health and Human Services 1970, Radiation Health Handbook, pp. 215-217.
[c]Snyder, W. S. (Chair) 1975, Report of the Task Group on Reference Man, ICRP 23 (1975), pp. 17, 346, Table 12
[d]Calculated from data in Footnoted reference c, pp. 219-220, Table 98. Assume eye is a sphere and surface area S

This approach was then used to convert available inhalation data for nerve and vesicant agents. The resulting age analysis of acute exposure effects generated a summary table of inhalation exposure estimates for observable (threshold) effects and fatalities ($LCt_{50}s$) in adult males and newborns (Table 3.3) and was used to compare possible exposure levels associated with each accident scenario. These two age groups are assumed to represent the extremes of population sensitivity to agent exposure. Note that inhalation exposures for a given biological end point are usually much less than the percutaneous exposures [e.g., $LCt_{50}$ for GB inhalation = 70 mg-min/m$^3$; $LCt_{50}$ for percutaneous GB exposure = 15,000 mg-min/m$^3$ (U.S. Department of the Army, 1974)]. Where observable effects were characterized by a range of values, the minimum was used for comparing scenario results.

Because agent GB is the most volatile agent in the unitary stockpile, it presents the largest potential for agent transport to off-post locations. VX is the most potent of the agents being considered and it is persistent; however it is much less volatile than GB and does not readily disperse. Equal quantities of GB and VX would affect different downwind areas. Mustard agents are considered the least potent of the agents being considered, because the $LCt_{50}$ inhalation exposure is so high (1500 mg-min/m$^3$) in comparison with the $LCt_{50}$ inhalation exposures for VX (30 mg-min/m$^3$) and GB (70 mg
-min/m$^3$). In addition, mustard agents are known carcinogens; any exposure may have latent effects that will require consideration in protective action planning and decision making.

## 3.3 CHARACTERIZING EMERGENCY RESPONSE

### 3.3.1 Decision To Warn

The decision to warn involves the detection and assessment of hazard, as well as the mobilization of decision makers and completion of the decision-making process. People and organizations differ in their ability to conduct and accomplish the activities that are crucial to the initiation of the emergency response process. Hence, the initiation of emergency response with the decision to warn is distributed over time into the accident depending on a variety of factors. Once the hazard has been detected, the extent of the hazard will have to be assessed to determine the nature of appropriate response. In the meantime, the timing of the decision to warn depends on the mobilization process, the number of people required to reach a decision, and the perception of the urgency required by the situation. The perception of urgency determines whether emergency decisions are accelerated to meet requirements of severe crises or extended over long periods when crises are considered less urgent.

Sorensen, et al. (1988) asked emergency managers from communities around the country to characterize the number of people that would need to be involved in emergency decisions. These reported estimates are provided by emergency managers based on their expectations of decision-making time assuming ideal or most likely conditions. These estimates are based on the experience, knowledge, perspective, and attitudes of emergency management personnel. In emergencies described as urgent, in terms of being "fast-moving events," emergency managers indicated that an average of two people would be involved in emergency decision making.
Emergency decision making

**Table 3.3. Estimated inhalation exposure levels for acute agent health effects in selected age classes and activity levels**

| Agent | Age/gender | Activity[a] level | Observed effects[b] (mg-min/m$^3$) | Fatal (mg-min/m$^3$)[c] |
|---|---|---|---|---|
| GB | Adult male | Light | 1–2 | 70 ($LCt_{50}$) |
| | Adult male | Resting | 2–4[d] | 100 ($LCt_{50}$) |
| | Newborn | Light | 0.2–0.5 | 33 ($LCt_{50}$) |
| | Newborn | Resting | 0.7–1.4[d] | 47 ($LCt_{50}$) |
| VX | Adult male | Light | 0.05–0.8[e] | 30 ($LCt_{50}$) |
| | Adult male | Resting | 0.09–1.6 | 36 ($LCt_{50}$) |
| | Newborn | Light | 0.02–0.4[e] | 14 ($LCt_{50}$) |
| | Newborn | Resting | 0.07–1.2 | 17 ($LCt_{50}$) |
| H/HD | Adult male | Unreported | — | 1500 ($LCt_{50}$) |
| | Newborn | Unreported | — | 702 ($LCt_{50}$) |

[a]Mild activity inhalation rates assumed for most of the day; resting activity inhalation levels are used when the population at risk is usually asleep (midnight to 5 a.m.).

[b]The observed effects range includes the estimated $ECt_{50}$ for miosis as well as the estimated population threshold for no neuromuscular effects (tremors).

[c]Fatal exposures are rounded to the nearest whole number. From data summarized in App. B of Chemical Stockpile Disposal Program Programmatic EIS (U.S. Department of the Army 1988) and assumptions of Table 3.2. GB $LCt_{50}$ of 70 mg-min/m$^3$ based on value cited in U.S. Department of the Army 1974, Chemical Agent Data Sheets, Vol. 1, EO-SR-74001, Edgewood Arsenal Special Report, Defense Technical Information Center, Alexandria, Va. The D2PC code considers the $LCt_{50}$ value for GB to be 50 mg-min/m$^3$.

[d]Calculated for resting inhalation rates (see Table 3.2).

[e]Calculated for light activity inhalation rates (see Table 3.2).

expanded to an average of five people in more "slowly developing" events. In fast-moving events, only one person was frequently reported to be required for decision making.

The impact of urgency reduces the estimates of the amount of time required not only to assemble the necessary people for decision making but also to make the decision once the people are assembled. These data indicate that decision making among community officials would take 15 to 20 min under ideal conditions. Rogers and Sorensen

(1988) examine relative effectiveness of emergency warning systems. They find that, even assuming better than ideal decision-making times of about 10 min, in fast-moving events many people in close proximity can be exposed before being warned. Most likely estimates of the amount of time required to make decisions to warn the public in an emergency averaged about 30 min in rapidly progressing events. Many factors can interfere with the mobilization of decision makers and the uncertainty in making the decision. Sorensen, et al. (1988) conclude that although communities are capable of making timely decisions in emergencies, there are no guarantees that timely decisions will be reached even when the situation warrants.

Reported behavioral data from thirteen community emergency responses to chemical emergencies document the length of time required to make a decision to warn the public. Eight of these 11 cases are described in more detail in Appendix D; three additional cases recommended evacuation to protect the public from potential harm, including emergency responses to a suspected pesticide spill in Olive Grove, Mississippi, a train derailment in Boone, Iowa, and a chemical spill at the Kelsey Hayes, in Whitesboro, New York. In addition, the timing of the decision to warn was estimated for the train derailments in Pittsburgh and Confluence, Pennsylvania. Based on these limited case studies Figure 3.2 presents the cumulative probability of deciding to warn the public as the event progresses.

In the Titan rocket explosion near Lompoc, California, the public was not warned and thereby a decision to warn was not reached. Because the uncertainty about the nature of the threat, the only people able to reach emergency management officials were told to remain indoors, including officials in charge of institutions. Hence, this case underscores the critical nature of the decision to warn in the warning process. Combined, these limited data indicate that a decision to warn the public was made in about half of these cases in 15 to 20 min, with about two-thirds reaching a decision to warn in about 30 min.

These data seem to indicate that emergency decision making can be compressed to meet urgency, but it is clear that the decision to warn the public is not instantaneous with the occurrence of the event. Advance planning can reduce the amount of time required for decision making by reducing the number of people required to make emergency decisions, identifying critical factors in the decision, accelerating mobilization of required people and resources, and outlining the framework for decision making in emergencies. For the purposes of evaluating protective actions for chemical emergencies, decision-making time may be characterized as a lag between an accidental occurrence and the initiation of the warning process.

### 3.3.2 Warning System Characterization

Warning people of impending danger involves two conceptually distinct aspects—alerting and notification. *Alerting* makes people aware of an imminent hazard. Alerting deals with the ability of emergency officials to make people aware of the threat. Alerting frequently involves the technical ability to break routine acoustic environments to cue people to seek additional information. In contrast, *notification* focuses on how people interpret the warning message. People's interpretation of the warning message is

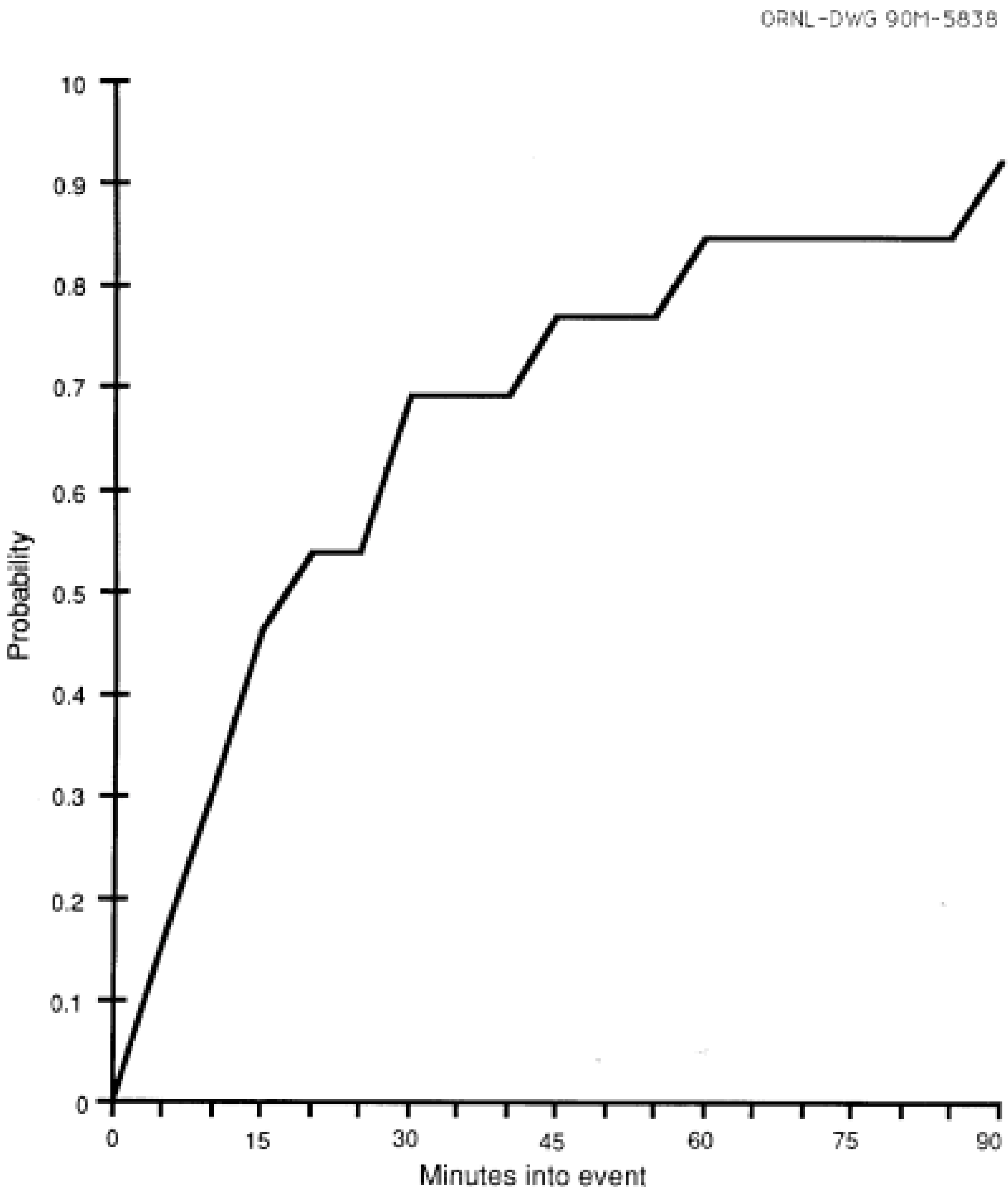


Fig. 3.2. Decision to warn public by time into event.

critically important in their selection of appropriate behavior in response to emergency warnings.

Emergency warning messages are received through a series of pathways that color their meaning. Some of this coloring is the result of cognitive processes; some is the result of the social structure. People interact with others, forming social networks, even though the forms of these networks vary. The routine and established nature of social networks has led to widely accepted generalizations concerning their function in society (Parsons 1951; Coleman et al. 1957; Granovetter 1973; Blau 1977; Burt 1987). Social networks also function in emergency situations and shape the response to emergency warnings. Two general propositions are strongly supported by the disaster literature (Williams 1964):

1. People respond to emergency warnings in the context of prior experience and the existing social and physical environs that interact with the warning message.
2. The extent to which the warning message is received depends on the nature of the warning message and the prior behaviors of all social actors, which are processed in the context of the social network.

This means that people have existing estimates of the threats presented by their environments. Furthermore, these estimates, together with personal experience, provide the basis for selecting behavior, that is, whether to accept, ignore, disseminate, challenge, or confirm the warning message (Baker 1979).

One of the results of an emergency warning is the recognition of threat, which creates psychological discomfort. Many people alleviate this discomfort by reducing the uncertainty associated with the message (Janis and Mann 1977). The warning process, described in Fig. 3.3, involves factors that affect both the message and the characteristics of the receiver (Rogers and Nehnevajsa 1987) or the sender and receiver (Mileti and Sorensen 1988). Once the warning is received, its content is evaluated in terms of the certainty and ambiguity associated with the event—its estimated severity, timing, and location of impact. This evaluation considers the likelihood of personal impact (will it affect me?), timing of impact (when will it occur?), and its anticipated effects (is the threat significant?) (Perry et al. 1981; Perry and Mushkatel 1984). The evaluation of the warning message leads to the determination of its relevance, which, in turn, leads to the perception of personal risk. If the message content is deemed irrelevant (I am not at risk), no emergency response is likely to ensue. However, should the warning message be considered relevant (I may be at risk), the message is processed in the context of prior disaster experience, relative proximity to the source of disaster, confidence in the source of warning, interpretation of the warning, and discussion with members of the social network. The warning message is processed in the context of the existing social structure, which leads to the initial perception of threat. The cumulative process provides the foundation for the selection and evaluation of emergency response behavior.

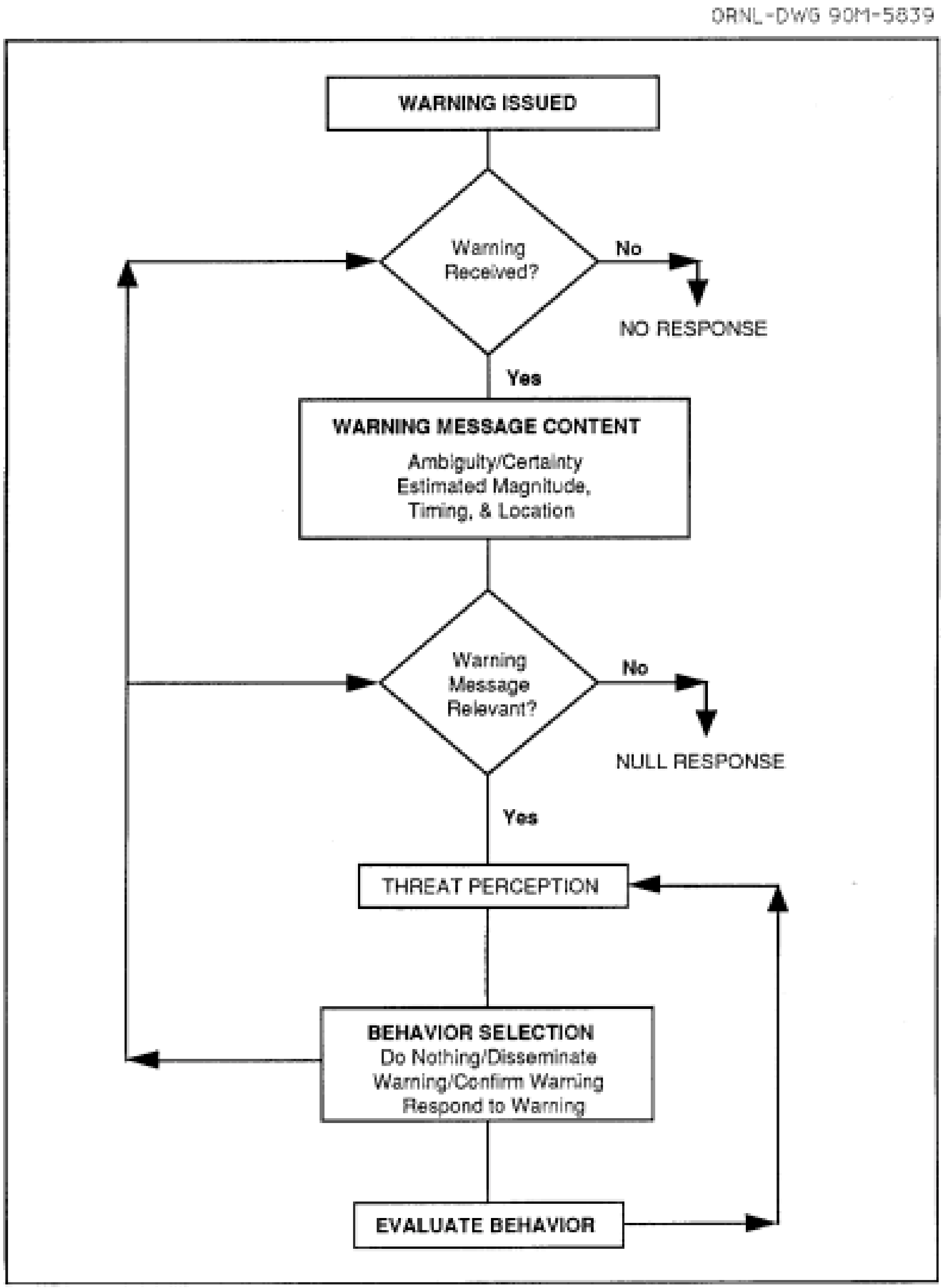


Fig. 3.3. Emergency warning and response process.

### 3.3.2.1 The Warning Process

The warning response process is not, however, a linear stimulus-response process (Mileti 1975). The first issuance of warning sets in motion an information-seeking process by which people attempt to confirm and reconfirm the contents of the warning (Leik et al. 1981), and to discover what friends, neighbors, or relatives are doing in response to the warning (Mileti and Sorensen 1987). As a result, members of the public become part of the informal warning system by disseminating the message further (Rogers and Nehnevajsa 1987).

Public response to emergency warnings is heavily influenced by warning content. Janis (1958) describes effective warning messages as requiring a balance between fear-arousing and fear-reducing statements. Fear-arousing statements provide sufficient description of the impending danger to evoke vivid mental images of the potential crises, which reduces the chance of surprise as the event evolves. Fear-reducing statements present the realistic mitigating factors of the situation while providing information concerning realistic responses by both authorities and individuals. The fear-arousing content of the warning message alerts the public to the potential for harm, whereas the fear-reducing content provides notification of appropriate avoidance, protective, and mitigative emergency actions. Empirical studies provide ample evidence of the message factors that shape response (Mileti and Sorensen 1987). These factors include credibility of the warning source; clarity, consistency, accuracy, and detail of the information; and frequency of the message issuance.

### 3.3.2.2 Diffusion of Emergency Warnings

The diffusion of emergency warnings resembles diffusion of other types of information or communications, except that it occurs in a shorter time period and the consequences of the warning not reaching the public can be devastating. The basic mathematical function is an S-curve or logistic function. The cumulative proportion of people receiving the warning forms an S-curve, which is determined by the exponential form of the initial alerting process and the logistic form of the subsequent contagion of the warning and message through the population (Rogers and Nehnevajsa 1987).

The alerting is characterized as a "broadcast process" that disseminates the emergency warning, which is centralized in the sense that many are alerted simultaneously. Contagion, on the other hand, is characterized as a "birth process" whereby people first hear of the event and then sequentially tell others (Lave and March 1975). The general mathematical specification of the diffusion curve is

$$dn/dt = k[a_1(N - n)] + (1 - k)\,[a_2 n(N - n)]\ ,$$

where k is the portion of the population alerted via the broadcast process, that is, the proportion of people who are alerted to the potential for harm who immediately recognize the meaning of the alert signal. The quantity (1 - k) represents the proportion of people left to be warned. The broadcast parameter, $a_1$, summarizes the efficiency of the alerting

process; the birth parameter, $a_2$, summarizes the effectiveness of the contagion process. N is the proportion of the population to be warned, and n is the proportion warned at the beginning of each period ($t_0$, $t_1$, . . .,$t_i$, . . .). Because each warning system provides differing degrees of information concerning the appropriate action to avoid, to protect oneself from harm, or to mitigate the potential for harm, the broadcast and birth parameters represent the dependence of each system on alerting and contagion, respectively. For example, the contagion parameter for a siren system will be relatively high because it requires recipients to take an active role in their own warning (i.e., they must do something). Usually this entails seeking further information via another (secondary) source.

### 3.3.2.3 Specifying the Diffusion Model

As with any simulation process, the selection of the parameters of the model is critical and tends to become the central focus of discussion of the simulation results. Alternative parameters for such simulations can be examined, adjusted, and analyzed as more empirical evidence becomes available.

The proportion of people receiving the alert signal and immediately recognizing its meaning, k, depends on the capability of the warning system to produce a signal that will be heard and understood immediately. The choice of k reflects the partition between people fully warned via the warning system (broadcast), including both alerting and notification, and those warned through contagion, requiring a secondary step of notification (birth). Warning systems that alert people to the potential for harm and that clearly and immediately notify them of appropriate protective action depend on the broadcast process. Telephone and tone-alert radio systems and systems combining telephones and tone-alert radios with sirens are the ones that are most dependent on the broadcast process. At the other end of the spectrum, siren systems depend on a second step in the warning process that requires the recipient to acquire information concerning appropriate action from another (secondary) source. Media-based systems are moderately dependent on the broadcast process.

Warning systems that include systems based on telephone and radio-alert are least dependent on the contagion process. Siren-based systems, however, are highly dependent on contagion in that people are not likely to know what to do. Media-based systems are moderately dependent on contagion. Because some members of society cannot be expected to understand the meaning of warning signals regardless of how effective they may be, all emergency warning systems depend on the contagion process to some extent. For example, no one expects children (below some ages) to comprehend the warning message and be able to carry out protective action. Dependency on contagion also occurs because of the complexity of the warning process. Emergency warning is not a simple stimulus-response situation. The simplified warning process depicted in Fig. 3.3 represents a complex of social and psychological processes suggesting that people will seek additional information to reduce uncertainty (e.g., Mileti and Sorensen 1987; Perry and Mushkatel 1984; Rogers and Nehnevajsa 1987).

The alerting parameter, $a_1$, is based on the efficiency of the broadcast process. It reflects the ability of the warning system to reduce uncertainty through the broadcast

process. The alerting parameter, $a_1$, represents the proportion of previously unwarned people who are warned (including both alerting and notification) during the period ($t_i$ to $t_{i+1}$) via the broadcast process. The selection of the exponential growth curve thus represents the efficiency of the broadcast process in providing complete warning.

The most efficient warning system is a telephone system because most people hear and answer telephones that ring. Furthermore, nearly all will listen to the message, particularly if the message makes it clear that "this is an emergency." The telephone system also offers the recipient two-way communication via information numbers, further reducing uncertainty by providing additional information. Tone-alert radios are slightly less efficient than telephones because some people will not hear the radio activate, some will have trouble understanding the message, and radios are one-way communication channels. Although these differences are subtle, they are likely to reduce efficiency. The media has a low alerting parameter because at any given time, including peak-use hours, the vast majority of people are not engaged with the electronic media. Media-based systems work only if the recipient happens to be listening at the time of warning. This means that people must tune in to the media before being warned. Siren systems are less efficient than other systems for a variety of reasons. The most important is the dependence of siren-based systems on an active participation in the warning process. People must do something immediately to find out which protective actions are required and how to take them. A number of factors contribute to one's not hearing the siren(s), not recognizing its meaning, or not recognizing that a warning situation exists when the siren is heard.

The contagion parameter, $a_2$, is based on the efficiency of the birth process. It reflects the ability of the warning system to reduce uncertainty through the contagion of warning. The contagion parameter, $a_2$, represents the proportion of previously unwarned people who are warned (including both alerting and notification) during the period ($t_i$ to $t_{i+1}$) via the birth process. The selection of the logistic growth curve represents the efficiency of the birth process in providing complete warning.

Siren systems are evaluated as being highly dependent on people's search for additional information to determine the meaning of the siren signal. However, once such information is sought, which is represented as (1 - k), the notification is assumed to be quite effective (i.e., $a_2$ is relatively high). This occurs because people actively seeking information are more receptive of the information provided (i.e., they are listening). Media-based warning systems are characterized by a process in which people hear a warning and tell others to listen. Hence, these systems are moderately dependent on the birth process for initial alerting, even though they are relatively effective at notification of what to do once people are tuned in. Both media- and siren-based systems depend on contagion (1 - k). However, the former requires contagion for initial alerting that an emergency exists, and the latter requires contagion for notification of appropriate protective actions to be taken. Because siren-based systems represent official warning, they are expected to be slightly more efficient when compared with media-based systems that require social network alerting. Systems based on tone-alert radios and auto dial telephones are least dependent on contagion (1 - k); in addition, these systems can provide information only to limited numbers of people at one time. They are therefore judged to have the least efficient contagion process, represented by low contagion parameters.

Based on judgments of the level of warning that could occur theoretically in the next 30 min ($t_i$ to $t_{i+30}$) under good warning conditions, limits on the diffusion rates were imposed. These limits were derived from some empirical observations and extrapolation of these observations (Sorensen and Mileti 1988). Because warning is a cumulative process, all systems are expected to warn almost 100% of the population at some point. The initial limits imposed on each system are presented in Table 3.4. To represent the cumulative nature of the process, the initial limits are gradually released throughout the warning period. This is equivalent to recognizing that the capability to warn people in the next 30 min depends in part on the number warned in previous periods. For example, warning in the next 30 min has only 30 min initially, but 10 min into the warning period, the cumulative warning window time is 40 min. The release rate values in Table 3.4 allow the limits imposed on each system to increase, approaching 100% of the population warned in the long run. Conceptually, the release rate characterizes the constraints associated with different warning systems.

Because of the synergistic effect associated with combined systems, the parameter specification for them selects the least restrictive release rate associated with the two combined systems. This reflects the complementary nature of the combined systems, providing the primary reason for using the two systems in conjunction. All emergency warning systems depend on the contagion process.

The warning penetration curves produced by using the parameters specified in Table 3.4 are illustrated in Fig. 3.4. The curves produce penetrations consistent with the available empirical data (Sorensen et al. 1988; Sorensen and Mileti 1988). At 15 min the portion of a population warned in an area covered by the warning system (or the probability that a person in the warning area has of receiving the warning) is highest for the combination of sirens and telephones but is not statistically different from that for the combination of sirens and tone alerts. Individually, the telephone and tone-alert systems have a slightly lower warning potential. Siren systems have a somewhat lower performance. Finally, the media-based system has the slowest rate of warning.

### 3.3.3 Public Response

Eliciting effective public response is the objective of the warning process. Hence, the public, as receiver of the warning message, is a fundamental element of the emergency response process. The public component of the process begins when information concerning a potential threat reaches the public, and it ends after the threat dissipates. Public officials may view the public warning process more bureaucratically by demarcating the public component with the decision to warn at one end and the public receipt of the "all clear" signal at the other. The following section discusses the receipt of a warning by the public, the response to warnings of chemical hazard, and the overall effectiveness of warning systems. The warning process is briefly discussed from the public's perspective.

#### 3.3.3.1 Responding to Emergency Warnings

Warning the public of the threat of an impending chemical hazard encompasses two steps: generating awareness of an abnormal set of circumstances characterized by an

**Table 3.4. Model parameters used to estimate warning diffusion**

| System | k | Alerting parameter Dependency | $a_1$ | Contagion parameter Dependency | $a_2$ | 30-min Limit | Release Rate (%) |
|---|---|---|---|---|---|---|---|
| Sirens | 0.2 | Low | 0.2 | High | 0.3 | 0.75 | 0.3 |
| Tone-alert radios | 0.4 | High | 0.3 | Low | 0.2 | 0.90 | 0.1 |
| Media | 0.3 | Low | 0.2 | Moderate | 0.25 | 0.50 | 0.5 |
| Telephones | 0.4 | Very High | 0.35 | Low | 0.2 | 0.93 | 0.1 |
| Siren and tone-alert | 0.4 | High | 0.3 | High | 0.3 | 0.95 | 0.1 |
| Siren and telephone | 0.4 | Very High | 0.35 | High | 0.3 | 0.95 | 0.1 |

*Source*: Rogers, G. O. and J. H. Sorensen 1988, "Diffusion of Emergency Warning," The Environmental Professional, Vol. 10, p. 281—294.

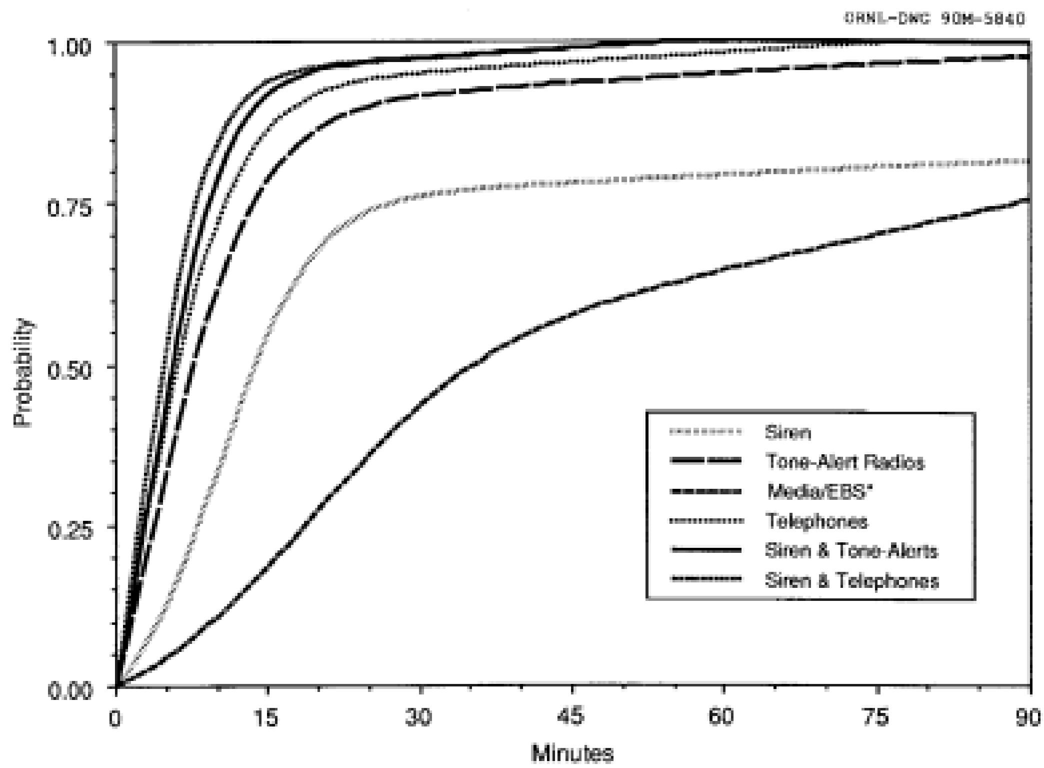


**Fig. 3.4. Probability of receiving warning by warning system by time elapsed since warning decision.** *Source*: G. O. Rogers and J. H. Sorensen, "Diffusion of Emergency Warning," *The Environmental Professional*, Vol. 10, p. 281–94, 1988. *Emergency Broadcast System.

elevated threat and providing information to elicit actions that minimize the dangers associated with the threat. The former is referred to as the alerting function; the latter constitutes the notification function. Alerting involves making the public aware that a hazard is imminent. Notification involves communicating the warning message to prompt mitigative response to the hazard. The central focus of alerting issues involves the technical ability to make people aware of the threat, and the primary notification issues focus on the public's interpretation of the warning message.

Warning messages are passed along a series of pathways that modifies their associated meaning. These pathways of warning communication involve cognitive functions and social structural considerations. The cognitive functions include the belief in the warning message, the personalization of the associated threat, the credibility of the source of warning, and the perception of the content. The social structural considerations involve the social context of the hazard, including the interactions with others in the social network, prior experience, extant social and physical environments, and existing conditions that interact with and influence the warning message. The response to an emergency warning is based on the degree of assessed hazard or danger, the threat, and the public's experience as placed in the social context. Therefore, the decision to accept, ignore, disseminate, challenge, or confirm the emergency warning message (Baker 1979) rests on this social context.

Psychologically, emergency warnings that result in the recognition of threat create discomfort and uncertainty of the impending event. The emergency warning process involves both the message and the characteristics of the receiver. Having received the message, it is evaluated in terms of certainty and whether the anticipated severity, timing, and location of impact are ambiguous. The message is personalized in terms of relevance: Is the threat likely to effect me? The resulting relevance of the warning message is determined in the context of prior disaster experience, relative proximity, credibility of the source of warning, interpretation, and discussion with others. Hence, the warning message is processed in the context of the social network.

Janis (1958) describes effective warning messages as those requiring a delicate balance between fear-arousing and fear-reducing statements. By describing the impending danger in sufficient detail, a vivid mental image of the impending crisis is evoked. This fear-arousing part of warning messages reduces the possibility of surprise and invokes response. The realistic presentation of the mitigating factors of the potentially threatening situation provides information regarding both the actions of authorities and those of individuals. This fear-reducing component of the warning message provides the foundation for adaptive response. "The fear-arousing content of the warning message alerts the public to the potential for harm, while the fear-reducing statements consist of notification of appropriate mitigation action" (Rogers and Nehnevajsa 1987: p. 358).

#### 3.3.3.2 Timing of Response

Response time may be characterized as the period between the time when people receive the warning message and the time when they take action to avoid harm. Timing public response to emergency warnings has been studied in conjunction with three train derailments, one in Mississauga, Ontario, another Pittsburgh, Pennsylvania, and a third in

Confluence, Pennsylvania. Figure 3.5 presents the cumulative proportion of people responding the emergency warning associated with three chemical accidents. Descriptions of these events are presented in Appendix E.

In all three emergencies, the principal response for individuals was to evacuate the affected area. In Mississauga, approximately 250,000 people were evacuated over a 4 d period (Burton et al. 1981). In Pittsburgh, about 22,000 people were evacuated (Federal Railroad Administration 1987). In Confluence, all 986 residents were evacuated (PEMA 1987).

The public's response to emergencies often begins spontaneously, before receiving an official warning. These three response functions are similar in that each approach complete response and generally is characterized as a logistic function or S-shaped curve. The response curve for the Confluence event climbs faster and reaches higher proportions responding than the other response curves. The Pittsburgh and Mississauga response curves are similar; however, the Mississauga curve is smoother due to the estimation procedures used by Burton et al. (1981). The Pittsburgh and Confluence curves represent raw empirical distributions.

Because of the steep response curve associated with the Confluence emergency, the response function closely follows the receipt of warning in the Confluence event; in Pittsburgh, response was both slower and more limited. This may result from the simply defined area at risk (i.e., the entire Borough of Confluence), the simply defined response options (i.e., evacuate to . . .), the vicarious experience of hearing about the evacuation in Pittsburgh, the perception and personalization of risk, or the social context associated with community size. The similarity of the Pittsburgh and Mississauga events, in terms of complexity (e.g., staged warning, size of population, population density, and demarcating evacuation zones), and the similarity of response curves suggest that the difference is more a function of complexity than any vicariousness associated with the timing of events.

For the purposes of evaluating protective actions for chemical emergencies, public response may be characterized in terms of the limited data regarding the timing of public response. Hence, the evaluation of protective actions during chemical events may assume that public response is similar to those responses characterizing the Mississauga, Pittsburgh, and Confluence events. Because each of these events took place in communities that have more or less typical emergency preparedness programs, and the unitary chemical stockpile communities are expected to have state-of-the-art systems, the evaluation system allows these response functions to be scaled up. For example, scaling up a response might be associated with public information programs; scaling down a response might represent complacency associated with a relative incident-free history. In addition, rather than constraining the response function to one of these events alone, the evaluator can average empirical curves. Finally, response can be characterized as complete at a particular moment into the warning process, which allows the evaluation of rapid response scenarios (for example, for evaluating the effectiveness of various actions associated with the response of institutional populations).

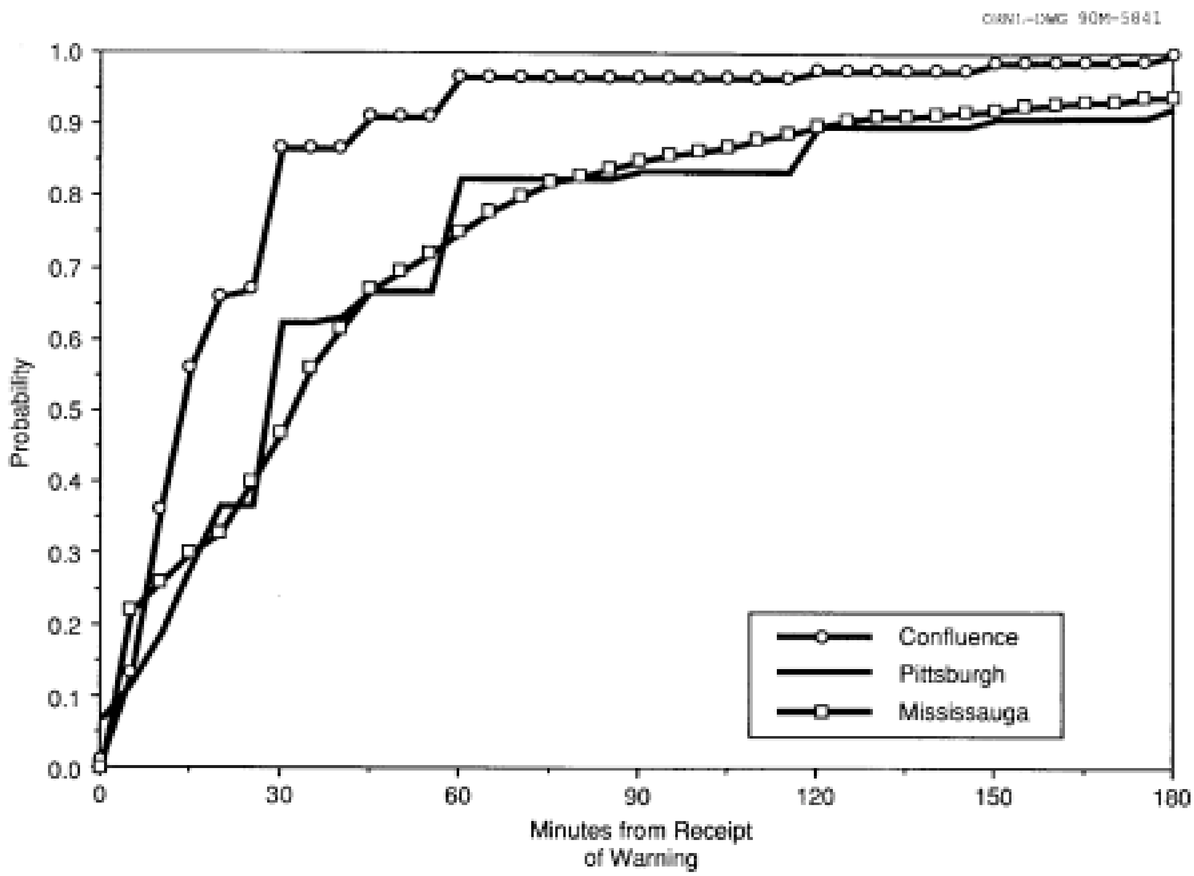


**Fig. 3.5. Probability of response after receipt of emergency warning in three chemical accidents.** Data for graph from I. Burton et al., *The Mississauga Evacuation, Final Report*, Institute for Environmental Studies, University of Toronto, Toronto, 1981; J. H. Sorensen, G. O. Rogers, and W. F. Clevenger, *Review of Public Alert Systems for Emergencies at Fixed Chemical Facilities*, ORNL/TM-10825, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1987.

### 3.3.4 Implementation of Protective Action

Under every emergency response scenario, the implementation of the selected protective action takes time. Hence, regardless of which protective action is being examined, implementation of the protective measure is distributed over time, beginning at the time of the decision to respond. Because each protective measure requires different sets of actions, implementation can be substantially different. Implementation may be categorized in terms of the associated protective action category: evacuation, in-place shelters, and respiratory devices.

#### 3.3.4.1 Evacuation

A number of approaches have been used to develop models and evacuation time estimates. A full modeling of the evacuation process involves data and assumptions associated with the origin-to-destination allocation of evacuees, the vehicle occupancy rates, the rate at which people respond to a threat or call to evacuate, and the nature of traffic movements over the network of available roads. Most of the analytical effort has been to develop acceptable traffic movement models, because this is the most complex component of the simulation process.

One of the simplest traffic movement models is an aggregation procedure that assumes a vehicle loading from a given region, assigns that load to routes, and estimates evacuation time by dividing the number of vehicles by road capacity estimates. Variations add other variables such as intersection delay times. This type of approach is used in some hurricane evacuation planning efforts. However, past experience with evacuation route analysis at ORNL and elsewhere indicates that evacuation times can be highly sensitive to network structure as well as to the temporal profile of evacuee response. Neither the fastest aggregate response to an alarm, nor the most evenly distributed traffic departure profile, is guaranteed to produce the lowest evacuation time for a given network and distribution of population. As a result, more elaborate modeling efforts were undertaken during the 1980s. These models increase in complexity, and also in data requirements, from simplified static (i.e., steady state) traffic route assignment models to more elaborate simulations based upon the detailed dynamics of traffic flow.

One of the earliest simulation models was developed for the U.S. Nuclear Regulatory Commission (NRC) to evaluate evacuation time estimates as part of the Final Safety Analysis Reports (FSARs). Referred to as the CLEAR model [Calculates Logical Evacuation and Response (Moeller et al. 1981; McLean et al. 1983)], it simulates individual vehicle departures and movement on a network given conditions of traffic volumes and flow. Incorporated are simplified procedures for handling vehicles at intersections, queuing delays, and travel velocities. Vehicles are loaded onto the network at intervals based upon an assumed (continuous) population distribution. Assumptions concerning preparation time also can be manipulated. CLEAR outputs include position of vehicles at any given time, vehicle population in given zones, and times to clear each zone.

More elaborate, origin-to-destination-specific traffic allocations linked to detailed route selection models also are available: notably, I-DYNEV (KLD Associates 1984), and

versions of the NETVAC (Sheffi et al. 1981, 1982), and MASSVAC computer codes (Radwan et al. 1985; Hobeika and Jamei 1985; Southworth and Chin 1987). In each case, researchers attempt to identify the best traffic routes for vehicles to follow out of the emergency planning zone (EPZ). In I-DYNEV, an equilibrium (static and deterministic) traffic route assignment algorithm is linked to a detailed traffic simulation model (TRAFLO) to replicate the travel time associated with single or multilane link and turning movements within the traffic flow. In contrast, both NETVAC and MASSVAC use forms of probabilistic dynamic traffic assignment routines that also incorporate turn movements by accounting for traffic discharge and loadings at intersections. The evacuation simulation model developed at Oklahoma State University by Tweedie et al. (1986) is also note worthy. Less detailed in its treatment of the highway network, it provides repeated Monte Carlo simulations of individual vehicle evacuations under congested traffic flow conditions, to develop statistical assessments of average and worst-case evacuation times.

Recent research has developed an alternative mathematical programming-based dynamic traffic assignment model (Janson In Press), that is more than simply an incremental assignment of traffic loadings at set intervals during the simulated evacuation. The volume of traffic on a given highway section can be identified as being composed of traffic from a variety of origins, possibly heading for different destinations, loaded onto the network at different starting times. By replacing the steady state assumption implicit in previous incremental and equilibrium traffic assignments, by allowing each traffic origination point to have its own temporal network loading profile, and by allowing traffic on any of the system's links to include vehicles from more than one loading interval, we are better able to assess the magnitude, location, and timing of downstream delays resulting from geographically and temporally varying (spontaneous as well as post-alarm) evacuation rates.

A second benefit of using a dynamic assignment approach is the possibility in the future of linking such a routine to observed traffic counts (from roadside counters and/or in-vehicle surveillance and monitoring software) from which real-time control of ongoing evacuations could be developed (Janson and Southworth 1989). The prototype RTMAS (Real-time Traffic Monitoring and Analysis System), currently under development for the Federal Emergency Management Agency (FEMA) allows traffic counts to be polled in this manner (Southworth et al. 1989). Even if traffic loadings currently do not exist at intervals of a few minutes for any of the 8 sites, average loadings can be used to calibrate what is, in effect, a static assignment, as now used by most transportation planning agencies. The analyst could then experiment with a variety of "what if" dynamic network loading scenarios to identify worst-case traffic peaking conditions.

Inputs to each of the above evacuation models include data on the lengths, design volumes, free-flow speeds, and traffic control (e.g., traffic light) characteristics of the links making up the roadway system. They also require vehicle occupancy and regional demographic data and assumptions concerning the timing of trip departures [i.e. the rate(s) at which evacuees will load onto the highway network]. Alternative approaches to modeling such vehicle loading (evacuee response) rates include the use of prespecified discrete and continuous (linear, logistic, etc.) loading rates. Both as a set and individually, the models are quite flexible, allowing users to study special problems, including selective

evacuation strategies, bad weather travel conditions, emergency traffic control, possible traffic obstructions, and alternative trip generation scheduling in various degrees of detail.

Irrespective of which modeling technique is employed, detailed evacuation time estimates involve collecting data regarding population, determining assumptions about the traffic network and formulating an estimation model (Urbanik 1981; Urbanik et al. 1980; Aldrich et al. 1978; Aldrich et al. 1979; Tweedie et al. 1986 and Walsh et al. 1983). These evacuation time estimates involve the estimation of clearance times for various populations at risk. Not having these detailed site-specific evacuation time estimates, PAECE allows the user to specify clearance time in one of two ways: (1) a straight-forward selection of the minute past the decision to respond when the evacuation will be complete (2) the calculation of the evacuation clearance time based on the average or minimum speed of egress compared with the distance to be traveled to attain protection. The latter approach assumes that the avenue of egress is in the worst possible direction—directly downwind—and that, until the safe distance is achieved, the exposure accumulates as if those people are located at the original point being evacuated.

### 3.3.4.2 In-place Protection

Implementing in-place shelters is a function of both the number and complexity of the activities required to create an effective shelter and the capability of the people attempting to carry out those activities. The capabilities of the people involved also directly impact the degree of infiltration reduction achievable. Unfortunately, little or no research is available that adequately represents either the cross section of housing characteristics needed to represent the complexity of the activities required to complete satisfactory in-place shelters, or the capabilities of the people required to implement the activities. While considerable research concerning the effectiveness of in-place shelters at reducing the amount of airborne toxics has been done (Birenzvige and Bartlet 1982; Birenzvige 1983a; Birenzvige 1983b; Bartlett and Birenzvige 1981; Gant and Schweitzer 1984; Lindell and Barnes 1985; RFF 1988; Wilson 1988a and 1988b; Witzig and Shillenn 1987), no systematic approach to achieving exposure reductions is widely accepted. For example, most research supports the basic finding that closing doors and windows will reduce infiltration but yields limited agreement concerning the degree of reduction attainable by taping cracks and sealing windows and gives no empirically based information regarding the amount of time it takes to implement either the former or the latter.

One unresolved implementation problem concerns the time it takes to close all doors and windows and turn off any air conditioning or heating system, which affect the filtration capacity of buildings. One particularly difficult problem in this regard is the use of wood or coal-burning stoves for heating. First, they are difficult to turn off, and second, many of them draw air for combustion from the indoor environment, which is replaced with air from the potentially contaminated outdoor environment. Even the number and distribution of doors and windows vary considerably from house to house, which means that the time it takes to implement even the most simple in-place protection measures varies. Another unresolved implementation problem involves the time it takes to augment the protection capacity of a dwelling by taping cracks and sealing windows and doors. Appendix F summarizes some preliminary expedient shelter trials conducted to

provide data regarding the timing and effectiveness of in-place shelters that rely on reduction of infiltration for protection. To conduct these trials draft instructions to tape and seal a room within a dwelling were developed (Appendix G). This preliminary research is reported in greater detail in Rogers, et al. (In Press).

The timing of two sets of actions required to implement in-place shelters that rely on reduced infiltration to provide protection were examined in the expedient shelter trials: (1) closing doors and windows and turning off heating and cooling systems and (2) taping and sealing a single room within a dwelling. Figure 3.6 summarizes the cumulative proportion of completing these activities by time into the trial. These limited data indicate that the average time it takes to simply close the doors and windows is 3.2 min, with a maximum of 6.1 min and a minimum of 2.3 min, and a median of 2.8 min [implementation times were recorded in 6 s (0.1 min) intervals]. These data indicate that the time it takes to tape and seal a room is likely to be considerably more, with an average implementation time of 16.7 min, a minimum of 2.3 min and a maximum of 38.6 min, and a median of 15.7 min.

Implementation times are cast in terms of closing exterior doors and windows, and turning off heating, cooling and circulation systems for normal, enhanced and pressurized in-place shelters described in Appendix C. Expedient shelters involves the taping and sealing of at least one room in addition to closing doors and windows, and turning off heating, cooling and circulation systems. In addition to these basic in-place sheltering requirements, evaluation of other implementation times requires the ability to set a time at which implementation is completed. Hence, PAECE allows the evaluator to select (1) closing doors and windows, which includes heating, cooling and circulation system shut-down, (2) taping and sealing a room in addition to closing doors and windows, or (3) select a time at which the implementation will be completed.

#### 3.3.4.3 Respiratory Protection

Donning a respiratory device involves first locating that device and then fitting it properly in place to afford protection to the person wearing it. Military personnel, once they have been trained, are expected to be capable of implementing these procedures in very rapid order—in as little as 6 or 7 s (personal communication; B. Reinert, Personnel Protection Studies Division, Los Alamos National Laboratory, to C. Griffith-Davis, Energy Division, Oak Ridge National Laboratory, July 26, 1989). Because the temporal resolution of PAECE is limited to 1 min intervals, this far exceeds the resolution available in the model. Hence, implementation of respiratory protection can occur at 1 min intervals, as selected by the evaluator.

## 3.4 CHARACTERIZING THE ENVIRONMENT

### 3.4.1 Time Budget

The location of people at various times of the day impacts two important aspects of emergency response: the ability of warning systems to penetrate to people in various locations, and the inherent protection provided by the current locations. The former deals

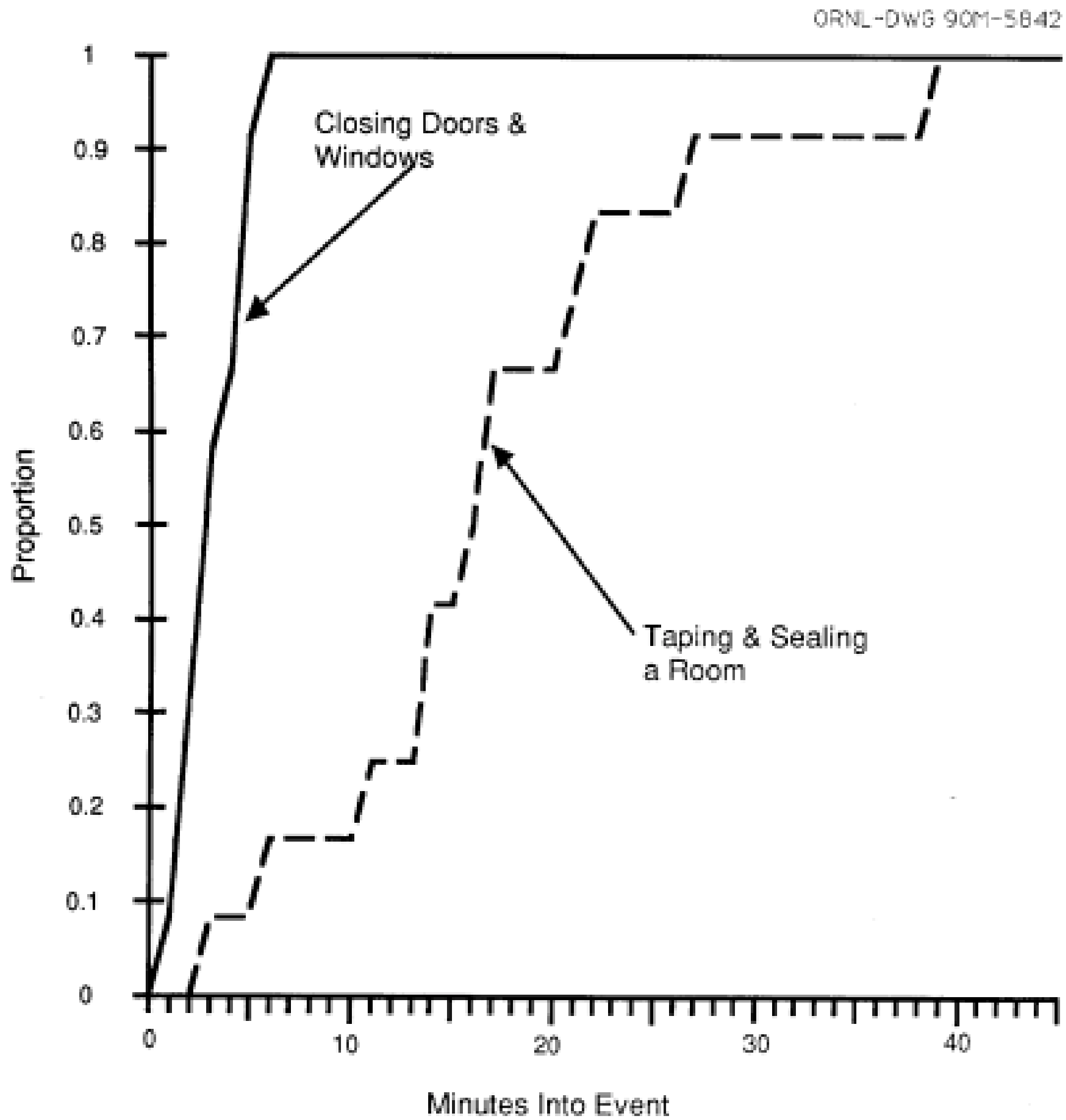


**Fig. 3.6. Probability of completing implementation of in-place procedures.**

with the ability of warning systems to alert and notify people in various locations, while the latter characterizes various locations by the protection they offer.

#### 3.4.1.1 Warning Penetration Adjustments

**Warning penetration**

Warning systems generally are characterized by their ability to alert people and transfer information. The penetration of the emergency warning systems varies for people in different locations and engaged in different activities. Each warning system has a different penetration capability in five fundamental locations/activities: (1) home asleep, (2) indoors at home or in the neighborhood, (3) outdoors in neighborhood, (4) in transit, and (5) working or shopping. In addition, two activities are allowed to override the other locations/activities, that is, watching television and listening to the radio. Such electronic-media exposed activities are relevant for warning because some of the systems depend on these forms of media. Figure 3.7 summarizes the average percentage of the population in these location/activity categories over a 24-h period starting with 12 midnight (Juster et al. 1983). Table 3.5 provides estimates of the percentage of the population reached by each warning system while engaged in the different activities. The following discussion provides the basis of these estimates.

**Home Asleep**. One of the most vulnerable positions, at least in terms of perception, occurs when people are at home asleep. In a regional survey, Nehnevajsa (1985) asked people what kinds of things awaken them at night, for example, between 2 a.m. and 4 a.m. The results indicated that 69.1% of the residents in southwestern Pennsylvania are aroused from sleep by sirens in their area, and 93.3% reported that telephone calls wake them up. These empirical data are used as estimates of the penetration rate for the siren and alarm and the telephone ring-down systems, respectively. Because tone-alert radios are similar to telephones but may or may not be physically located in the bedroom, as many phones are, the penetration rate for tone-alert radios is estimated at 85%. Furthermore, because media and the emergency broadcast system are relatively dependent on having either a radio or a television on at the time of warning and because most people do not sleep with them on, the penetration rate is assumed to be zero for media/Emergency Broadcast System (EBS) warning systems.

**Indoors at home or in neighborhood**. Residential indoor locations are categorized together. This includes nonsleeping activities in residential locations in the area at risk. The penetration rates are assumed to resemble the pattern for sleeping conditions but to be somewhat higher for nonsleeping activities. However, when people are awake, even though they may not be watching television or listening to the radio, they may be warned by others. For this reason, the media/EBS warning system is assumed to be 40% effective.

**Outdoors in neighborhood**. Siren systems are very effective in reaching people in outdoor environments, although some people will not hear sirens because of background noises. Overall, it is estimated that 90% of the people outdoors will hear the siren. Because people outdoors are very unlikely to hear an indoor-based warning system, it is assumed that no one outdoors hears a warning when tone-alert or auto-dial telephone systems are being considered. The effectiveness of media will also be low for people

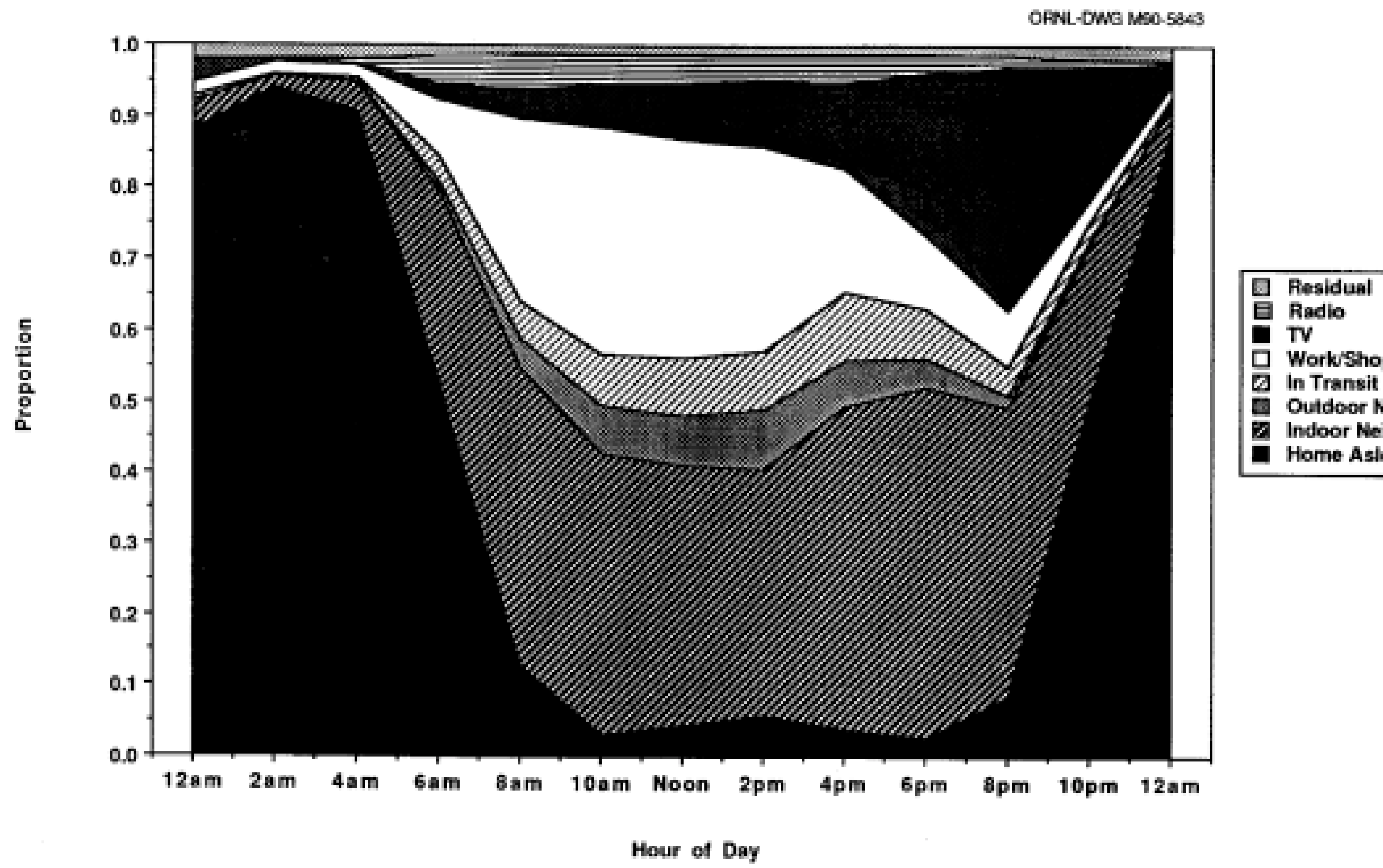


Fig. 3.7. Average U.S. time budget with secondary media activities overriding.

**Table 3.5. Warning systems effectiveness by location and activity**

| Location/ activities | Alternative warning system: Sirens and alarms | Tone-alert radios | Auto-dial telephones | EBS/ media | Siren and alarm systems combined with: Tone-alert radios | Auto-dial telephones |
|---|---|---|---|---|---|---|
| Home asleep[a] | 0.691 | 0.85 | 0.933 | 0.0 | 0.90 | 0.933 |
| Indoors at home/in neighborhood | 0.80 | 0.90 | 0.95 | 0.40 | 0.90 | 0.95 |
| Outdoors in neighborhood | 0.90 | 0.0 | 0.0 | 0.20 | 0.90 | 0.90 |
| In transit | 0.90 | 0.0 | 0.0 | 0.20 | 0.90 | 0.90 |
| Working or shopping | 0.60 | 0.70 | 0.80 | 0.10 | 0.70 | 0.80 |
| Television | n/a | n/a | n/a | 1.0 | n/a | n/a |
| Radio | n/a | n/a | n/a | 1.0 | n/a | n/a |
| **Time-adjusted warning system effectiveness** | | | | | | |
| Annual average | 0.665 | 0.685 | 0.745 | 0.287 | 0.784 | 0.826 |

[a]Reported arousal by sirens and telephones is derived from a survey by the University of Pittsburgh, Center for Social and Urban Research, in 1985, from Nehnevajsa 1985.

*Source*: Rogers, G. O. and J. H. Sorensen 1988, "Diffusion of Emergency Warning," The Environmental Professional, Vol. 10, p. 281—294.

outdoors. However, it is likely that some people will be listening to the radio while engaged in other activities. This is conservatively estimated at 25%.

**In transit**. Most people in vehicles are likely to hear a siren within a warning zone (Towers et al. 1982); therefore, the portion receiving the alert is estimated to be 90%. No one in a vehicle is able to hear either the tone alert or the telephone warning. A portion of those in transit will be listening to the radio; hence, this fraction is defined as 20%.

**Working or shopping**. Sirens will have a lower effectiveness in alerting people who are working or shopping, because of background noise and poor attenuation of sound into buildings housing those activities. It is estimated that about 60% will hear the warning. Shops and places of employment can be provided with tone-alert radios and telephone warning systems. However, the penetration of warning through these systems is likely to be lower than for home environments. In addition, the telephone systems are likely to be more effective than tone-alert systems because people in shopping and work locations are more likely to answer their phones than to be near a tone-alert radio. Few people engaged in shopping or work will receive a media-disseminated warning unless they are listening to a radio station at the time.

**Watching television and listening to radio (primary and secondary)**. It is assumed that 100% of the people engaged in activities involving exposure to the media, such as watching television or listening to the radio, will receive a warning.

**Time budget surveys**

In 1975, the Survey Research Center at the University of Michigan administered a time budget survey to a national probability sample of U.S. households (Robinson 1977). The same households participated in a second panel of the same survey in 1981 (Juster et al. 1983). Although some panel attrition occurred between the 1975 and 1981 portions of the study, a comparison of the two studies indicates that the attrition in sample sizes caused little, if any, bias in the results. Controlling for demographic variables indicates that the time budgets of U.S. households were amazingly stable over this period of time (Hummon et al. 1987). The results in this study are from an analysis of the 1981 panel data.

Respondents were asked to construct a 1-d (24-h) log of their activities during the previous day. The two weekdays and two weekend days of data for each survey year are combined and weighted to estimate how Americans spend time over an annual average week—a "synthetic week" (Stafford and Duncan 1980; Stafford 1980). However, the synthetic week approach does not provide enough detail about the daily schedules of people for risk analysis and emergency management (Hummon et at., 1987). This analysis uses a daily schedule data structure.

Each type of warning system is evaluated in terms of the likelihood that people in the different locations will be warned; the locational capabilities of each system are mapped onto the probability that people will be in these locations at various times of the day. This mapping of locational system effectiveness on the likelihood of the presence of people in these locations provides a relative effectiveness in terms of the likelihood that people will be engaged in various activities in various locations (Table 3.5).

The warning dissemination process is adjusted to account for time-dependent activities by multiplying the location activity adjustment factor in Table 3.5 by the average portion of the population engaged in each activity in a 24-h period. This value represents

the portion of the population in each activity assumed to receive the warning. Second, this is summed for each warning system to achieve the time-adjusted warning system effectiveness score. This score is then used to weight the original alerting parameter ($a_1$) in the diffusion model. This weighting reduces the influence that the initial alert has on diffusion according to the average distribution of people in various activities who would not receive an initial alert. This procedure was used to produce time-specific curves to reflect the locations/activities of the population for any 2-h period.

#### 3.4.1.2 Protective Action Implementation Adjustments

The average time budget data also are used to adjust the amount of "natural" protection various locations provide. This adjusts initial exposures to account for the fact that some environments that people frequent provide minimal protection. The most important of these are indoor locations. Being indoors, particularly in cool or cold weather, buildings already would be closed up and would provide protection commensurate with the amount of infiltration associated with that building. On the one hand, complete maximum protection cannot be achieved passively; however, just because people are already in enclosed environments they are not completely unprotected.

The current evaluation of protective actions for chemical emergencies takes advantage of the protection afforded by indoor locations by initializing the implementation of in-place shelters with the probability of being located in a partially protected location at the time of release. Hence, for relatively passive in-place sheltering techniques (e.g., normal and enhanced shelters), during periods of the year when doors and windows would be closed naturally, the shelter is already implemented for people in those buildings. The degree of protection in these partial shelters is accounted for by higher infiltration rates.

The implementation of an in-place shelter is initialized at the probability of being located indoors (see Fig. 3.8). This means that the proportion of people implementing the action is initiated at more than 90% for accidents at 2 a.m., while initial midday implementation of normal and enhanced shelters is about 50%.

### 3.4.2 Meteorology

The meteorological conditions for the eight storage locations are summarized in Table 3.6. The dominant meteorological condition is characterized by a D stability and moderate winds. This condition occurs an average of 44% of the time and is typically characterized by 5.5-m/s winds. While no meteorological condition can be ignored, emergency management programs must account for the most likely conditions to occur. Meteorological states characterized by very stable conditions and low wind speeds occur typically at night and generally lead to longer plumes and greater concentrations of agent. Fortunately, these conditions also allow more time for emergency response. Moderate stability classes and midrange wind speeds generally lead to shorter plume lengths and lower concentrations but faster onset times. While the conditions presented in Table 3.6 focus on the types of meteorological conditions observed at each site, they cannot represent the rare circumstances that sometimes occur. Emergency managers must

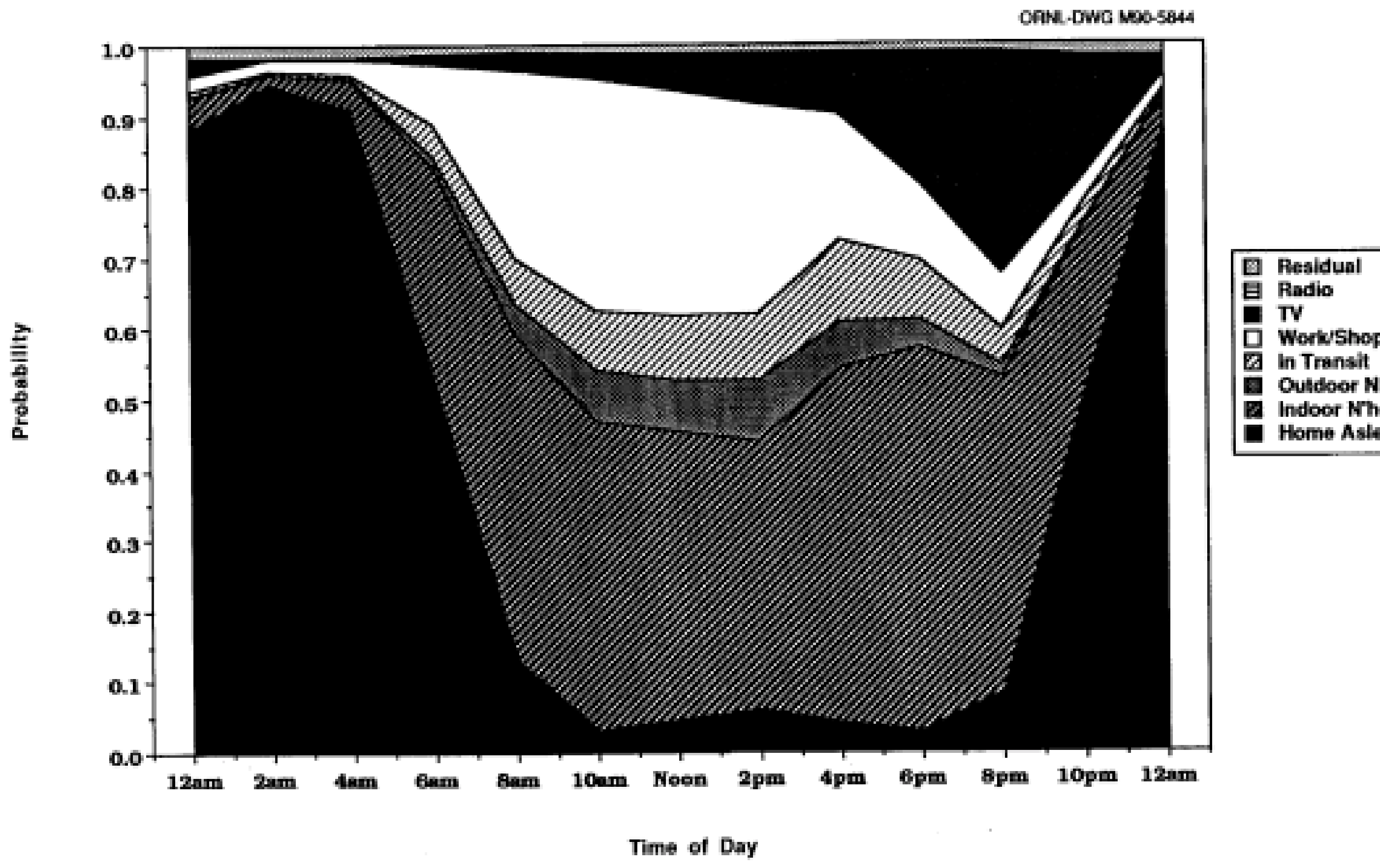


Fig. 3.8. Average U.S. time budget of primary activities.

**Table 3.6. Percent of observed meteorological conditions by stability class by site**

| Stability class[a] | APG | ANAD | LBAD | NAAP | PBA | PUDA | TEAD | UMDA |
|---|---|---|---|---|---|---|---|---|
| A, Average WS[b], m/s | 0.7 (1.68) | 0.6 (1.99) | 0.5 (2.20) | 0.7 (1.92) | 6.4 (1.92) | 0.8 (1.81) | 1.4 (2.41) | 1.1 (1.67) |
| B, Average WS, m/s | 4.4 (2.74) | 4.8 (2.69) | 4.4 (3.00) | 4.9 (2.93) | 10.8 (2.77) | 8.2 (2.56) | 8.6 (3.03) | 9.2 (1.96) |
| C, Average WS, m/s | 11.5 (3.76) | 13.5 (3.29) | 11.6 (3.80) | 10.7 (3.90) | 21.0 (3.35) | 13.9 (3.87) | 13.9 (3.25) | 10.3 (2.82) |
| D, Average WS, m/s | 50.3 (6.46) | 40.9 (4.05) | 53.0 (4.65) | 52.1 (4.93) | 32.0 (3.07) | 39.6 (6.04) | 35.2 (4.28) | 52.6 (4.43) |
| E, Average WS, m/s | 13.5 (3.14) | 14.2 (3.71) | 14.4 (3.11) | 12.8 (3.25) | 16.0 (1.71) | 16.2 (3.45) | 19.6 (1.51) | 10.7 (3.02) |
| F, Average WS, m/s | 12.4 (2.04) | 17.0 (3.51) | 12.6 (2.41) | 12.6 (2.32) | 13.8 (.57) | 14.3 (2.34) | 21.4 (.73) | 8.5 (1.87) |
| G, Average WS, m/s | 7.2 (1.11) | 9.0 (3.20) | 3.5 (1.28) | 6.2 (1.11) | **[c] **[c] | 7.0 (1.17) | **[c] **[c] | 7.6 (1.30) |

[a]Stability classes are used to represent the extent of atmospheric turbulence at the location at the time of the accident. Several widely used classification schemes are available. The most widely used scheme was originally proposed by Pasquill (1961), for diffusion from low-level, nonbuoyant sources over open country. The categories of stability class are: (A) extremely unstable conditions, (B) moderately unstable conditions, (C) slightly unstable conditions, (D) neutral conditions, (E) slightly stable conditions, (F) moderately stable conditions, and (G) extremely stable conditions. Gifford (1976) examines modifications to Pasquill's scheme to account for elevated and buoyant releases, boundary-layer stability, and diffusion over great distances.

[b]Average wind speed.

[c]Only 6 stability classes (A–F) were used at this site.

prepare for all potential conditions but can give more attention to emergency preparedness for conditions observed more frequently.

### 3.4.3 Population Distribution

The most recent residential population data are summarized in Table 3.7 for areas within 35 km of each storage location. Nearly 20,000 people live within 5 km of a storage locations but less than 1% of the people residing within 35 km reside within 5 km. The largest relative concentration of people living within 5 km is at LBAD, where 1.3% of the nearly 130,000 people residing within 35 km live within 35 km. Included among sites with larger relative concentration of population residing within 5 km are ANAD and APG with 1.2% each and PBA and UMDA with 1.1% each.

An average of 6.8% of the people living within 35 km live between 5 and 10 km from the storage locations, and this represents nearly 90,000 people program wide. Again, LBAD is characterized by the largest relative concentration, with 19.4% in the 5- to 10-km annular ring. UMDA and ANAD have more than 10% each, with 12.9% and 10.1% respectively, living in the 5- to 10-km ring. LBAD, UMDA, and ANAD have above average relative concentrations of people within 10 km; however, the absolute concentration of people at APG is larger than any other site, with more than 30,000 people living within 10 km. All eight sites have larger relative concentrations in the 10- to 20-km and 20- to 35-km annular rings than in areas located more closely. Approximately 30% of the people live between 10 and 20 km from the storage location on the average; about 63% live between 20 and 35 km from the storage locations.

An effective emergency response strategy must protect all parties requiring protection. In this sense, the relative distribution of population, or even the absolute population distribution, is irrelevant. Effective emergency management programs must, however, distribute appropriate protection measures to those requiring protection. Hence, officials may be able to have more intense training, use more expensive protection devices, and provide more maintenance or better communications systems to achieve adequate protection to people located in close proximity compared with people located farther away.

For the purpose of this analysis, population is represented by the proportion of the total population at a given distance—the affected people. In this way, any population concentration may be represented by that proportion simply by multiplying the proportion by the number of people in the area. This representation is appropriate for a programmatic analysis; it keeps the analysis generic and avoids potential complications associated with the valuation of life.

**Table 3.7. Population distribution near unitary chemical agent storage facilities in continental United States**

| Site | Downwind distance category: Less than 5 km | 5 to 10 km | 10 to 20 km | 20 to 35 km | Total within 35 km |
|---|---|---|---|---|---|
| ANAD, % | 1.2 | 10.1 | 41.5 | 47.2 | 196,925 |
| APG, % | 1.2 | 2.7 | 14.1 | 82.0 | 1,134,038 |
| LBAD, % | 1.3 | 19.4 | 23.3 | 56.1 | 129,969 |
| NAAP, % | 0.9 | 3.5 | 16.2 | 79.4 | 101,872 |
| PBA, % | 1.1 | 4.7 | 60.9 | 33.3 | 113,041 |
| PUDA, % | 0.1 | 0.3 | 4.5 | 95.1 | 116,234 |
| TEAD, % | 0.0 | 0.5 | 4.6 | 94.8 | 20,404 |
| UMDA, % | 1.1 | 6.8 | 29.4 | 63.0 | 28,870 |
| Average, % | 0.9 | 6.8 | 29.4 | 63.0 | 230,169 |
| Standard deviation, % | 0.5 | 6.3 | 23.6 | 27.6 | 345,653 |
| Program total | 19,765 | 89,211 | 383,483 | 1,348,894 | 1,841,353 |

*Source*: Population statistics are the latest available (S. A. Carnes et al., Oak Ridge National Laboratory, Oak Ridge, Tenn., 1989): "Emergency Response Concept Plan for Pine Bluff Arsenal and Vicinity," ORNL/TM-11092; "Emergency Response Concept Plan for Anniston Army Depot and Vicinity," ORNL/TM-11093; "Emergency Response Concept Plan for Tooele Army Depot and Vicinity," ORNL/TM-11094; "Emergency Response Concept Plan for Newport Army Ammunition Plan and Vicinity," ORNL/TM-11095; "Emergency Response Concept Plan for Aberdeen Proving Ground and Vicinity," ORNL/TM-11096; "Emergency Response Concept Plan for Umatilla Depot Activity and Vicinity," ORNL/TM-11097; "Emergency Response Concept Plan for Pueblo Depot Activity and Vicinity," ORNL/TM-11098; "Emergency Response Concept Plan for Lexington-Blue Grass Army Depot and Vicinity," ORNL/TM-11099.

# 4. DATA AND METHODS

This section discusses the data and methods used herein. It first describes the distribution of accidents and accident scenario selection to underscore the realistic portrayal of potential accidents. Secondly, this section presents the model developed to evaluate protective actions, PAECE, and the measures of protective action effectiveness employed. Hence, this section focuses both on analysis and model development.

The universe of potential accidents relevant to the storage and disposal of the unitary chemical stockpile is very large. The thousands of potential accidents identified by the risk analysis for the CSDP (Fraize et al. 1987) at the eight storage sites could be multiplied many times by considering additional variance in prevailing meteorological conditions, downwind distance, time of day, warning system used, decision-making time, and toxicological end points (e.g., fatal or incapacitating exposures). To simplify the problem of considering such an array of potential accidents, several representative accidents were selected for preliminary analysis. The following section identifies the accidents selected for analysis and discusses the principal variables embedded in the evaluation. Section 4.2 describes the model used to evaluate protective action effectiveness in this analysis and Sect. 4.3 describes the process of analysis and the interpretation of results.

## 4.1 SAMPLING MODEL RESULTS

Potential accidents are selected with special emphasis on inhalation pathways to represent the range of agent types, release events, duration, and source strengths (quantity). An atmospheric dispersion model, the D2PC (Whitacre et al. 1987), is used to estimate the lethal downwind distance of each accidental release. Given the relatively high volatility of GB agent and the concern over inhalation exposures, GB accidents are initially evaluated; however, accidents involving all agents are considered.

### 4.1.1 Planning Base Accidents

The various planning base accidents considered in the evaluation of protective action alternatives are summarized in terms of initiating events and location in Table 4.1. These accidents have the potential to occur with various agents, munitions, and quantities of agent and are used to represent a distribution of potential accidents that contains more than 500 specific events. These accident sequences represent all the major locations for potential accidents identified in the CSDP risk analysis (Fraize et al. 1988), and include initiating events that are the direct result of storage and disposal operations (internal events) and initiating events that stem from nonstorage or disposal activity (external events).

**Table 4.1. Planning base accidents represented for evaluating protective actions**

| Accident code | Location of accident | Brief description of accident |
|---|---|---|
| HF 3 | Disposal plant | Forklift collision accident with fire |
| HF 7 | Disposal plant | Collision accident, no fire |
| HF 11 | Disposal plant | Munition pallet dropped with detonation |
| HF 13 | Disposal plant | Munition pallet (in container) dropped with detonation |
| HO 12 | Not at plant | Forklift collision with detonation |
| HS 5 | Long-term storage | Munition dropped with detonation |
| PO 13[a] | Disposal plant | Large aircraft crash with fire |
| PO 29[a] | Disposal plant | Earthquake damages plant with fire |
| PO 33[a] | Disposal plant | Earthquake results in falling munitions |
| PO 49 | Disposal plant | Munition detonation causes structural and ventilation system failure |
| PO 52 | Disposal plant | Burstered munition put in incinerator |
| SL 4[a] | Long-term storage | Direct crash of large aircraft into storage area with fire |
| SL 5 | Long-term storage | Indirect crash of large aircraft, causing fire |
| SL 15[a] | Long-term storage | Direct crash of small aircraft into storage warehouse or open storage, causing fire |
| SL 16[a] | Long-term storage | Large aircraft crash, no fire; burstered munitions detonate |
| SL 26[a] | Long-term storage | Earthquake causes fire in warehouse |
| SL 28[a] | Long-term storage | Earthquake causes fire in warehouse |
| VO 4 | On-site transport | Munitions vehicle accident with fire & detonation |

[a]Event not the result of storage or disposal operations.

#### 4.1.1.1 GB Accidents

For agent GB, the potential accidents are partitioned into the five classes of accidents presented in Table 4.2. Because the driving factor in evaluating protective action is what people are to be protected from, the estimated exposure becomes critical. Moreover, because the estimated exposure for a given meteorological condition (via plume dispersion) rests firmly on the quantity released, the accident classes used herein are based on the quantity of agent released. These accident classes are arranged in descending order from the most catastrophic to the least problematic.

The GB Class V accidents are catastrophic and initiated by external events. An aircraft crash that releases more than 13,000 lbs (nearly 6000 kg) of GB would fall into this category. This accident is estimated to last 20 min, has a no-deaths downwind distance of more than 20 km under 3-m/s winds, and could impact human populations more than 100 km from the release point.

The GB Class IV accidents also result from external events, releasing approximately 900 to 2075 lbs (400 to 940 kg) of agent GB. Accidents in this category are expected to continue over the entire first 3 h (because they actually range from 240 to 360 min) and potentially to affect people between 3 and 11 km under 3-m/s winds, with potential impacts to 50 km. This class of accidents is represented by the accident in the category with largest release of agent, SL 16, which is characterized by a large airplane crash in the storage area.

The GB Class III accidents include both internal and external initiating events and range in amount of agent released from approximately 170 to 315 lbs (80 to 140 kg). Accidents in this category occur over a 20- to 360-min period and have no-deaths downwind distances from 3 to 5 km under 3-m/s winds and could impact people as far away as 20 km. This category of accidents is represented by the accident in the category with the largest quantity released, PO 13, which is characterized by a large airplane crash into the disposal facility.

GB Class II accidents include both internal and external initiating events, and range in amount of agent release from approximately 70 to 165 lbs (30 to 70 kg). Accidents in this category are of 20- to 360-min in duration, have associated no deaths downwind distances of from 1 to 3 km under 3 m/s winds, and could result in fatalities out to approximately 12 km under stable meteorological conditions. This category of accidents is represented by the potential Class II accident with the largest amount of GB released, VO 4, which is characterized by a munitions vehicle accident resulting in a fire.

GB Class I accidents result from storage and disposal operations initiating events, and involve from 2 to 53 lbs (1 to 20 kg) of agent. Some of the accidents in the category are instantaneous, while others last as long as 60 min. The no-deaths downwind distances range from about 1 to 2 km, under 3-m/s winds, and can result in fatalities as far away as 6 km under stable conditions. The largest quantity of agent released by an accident in this category occurs for accident HF 11 characterized by a dropped pallet of munitions in the disposal facility, and it used to represent the category.

**Table 4.2. GB accident categories and selected accidents**

| Accidents in catagory[a] | Quantity released (kg) | Duration (min) | No deaths downwind distance[b] (km) |
|---|---|---|---|
| **GB Class V** | | | |
| SL 4, SL 5 | 6,000 | 20 | 23 |
| **GB Class IV** | | | |
| SL 16, PO 29 | 410 to 940 | 240 to 360 | 3 to 11 |
| **GB Class III** | | | |
| PO13, PO 29, VO 4, PO 33 | 80 to 140 | 20 to 360 | 3 to 5 |
| **GB Class II** | | | |
| VO 4, HF 3, PO 29, PO 33, HF 7 | 30 to 70 | 20 to 360 | 1 to 3 |
| **GB Class I** | | | |
| HF 11, VO 4, HO 12, HS 5, PO 49, PO 52, HF 13 | 1 to 20 | 0 to 60 | 1 to 2 |

[a]The first accident listed in each class has the largest quantity released and is selected to represent the category.

[b]No-death distance is the length of the plume contour at which the expected concentration is less than the lethal concentration for adult males (i.e., 6 mg/m$^3$), given that 3-m/s winds and D stability prevail. Stability classes are used to represent the extent of atmospheric turbulence at the location at the time of the accident. Several widely used classification schemes are available. The most widely used scheme was originally proposed by Pasquill (1961), for diffusion from low-level, nonbuoyant sources over open country. The categories of stability class are: (A) extremely unstable conditions, (B) moderately unstable conditions, (C) slightly unstable conditions, (D) neutral conditions, (E) slightly stable conditions, (F) moderately stable conditions, and (G) extremely stable conditions. Gifford (1976) examines modifications to Pasquill's scheme to account for elevated and buoyant releases, boundary-layer stability, and diffusion over great distances.

#### 4.1.1.2 VX Accidents

For agent VX, the potential accidents are partitioned into five classes of accidents presented in Table 4.3. Like the GB accident classes, the quantity released is the driving factor in estimating exposure and thereby is used to categorize accidents. Unlike GB, VX usually requires a fire, explosion, or munition detonation to vaporize. Hence, to result in significant off-post exposures, the accident sequence involves either a fire or explosion or both. Accident classes are discussed in descending order, with the potentially most catastrophic accidents first and the least problematic last.

The VX Class V accidents are the result of external events releasing between 16,500 and 75,000 lbs (7,560 to 34,100 kg) of VX. These catastrophic releases are expected to be the result of external events lasting 20 to 360 min and to have a no deaths downwind distance of about 30 km under 3-m/s winds. Such release could impact human populations more than 100 km from the release point under more stable meteorological conditions. This category of accidents is represented by fire in a warehouse caused by an earthquake, SL 26, which is the largest amount of agent released by any accident involving VX.

The VX Class IV accidents also result from aircraft crashes that are expected to release from approximately 1,250 to 2,050 lbs (560 to 920 kg) of agent VX. Accidents in this category are anticipated to be from 30 to 240 min in duration and potentially to affect people between 9 and 11 km under 3-m/s winds, with potential impacts reaching about 50 km. This class of accidents is represented by the accident in the category with largest release of agent, SL 15, which is characterized as a small aircraft crash into an open strange area.

The VX Class III accidents include both internal and external initiating events and range in amount of agent potentially released from approximately 200 to more than 800 lbs (90 to 380 kg). Accidents in this category occur over a 20-min to 6-h period, are expected to result in no-deaths downwind distances from 2 to 8 km under 3 m/s winds and could impact people as far away as 35 km. This category of accidents is represented by the accident in the category with the largest quantity released, VO 4 (a munitions vehicle crash).

VX Class II accidents include both internal and external initiating events and are expected to range in amount of agent release from approximately 34 to 175 lbs (15 to 80 kg). Accidents in this category are from 20 to 360 min in duration, have associated no-deaths downwind distances of from 2 to 4 km under 3-m/s winds, and could result in fatalities out to approximately 14 km under stable meteorological conditions. This category of accidents is represented by the potential accident in the category with the largest amount of VX released, VO 4, a munitions vehicle crash resulting in a fire.

VX Class I accidents result from storage and disposal operations initiating events and are expected to involve from 6 to 31 lbs (3 to 10 kg) of agent. Some of the accidents in the category are instantaneous, while others last as long as 60 min. The estimated no deaths downwind distances are about 1 km, under 3-m/s winds. Fatalities could as far away as 5 km under stable conditions. Within the category, the largest quantity of agent released occurs when a munitions pallet is dropped in the disposal facility resulting in detonation (HF 11), and it is used to represent the category.

Table 4.3. VX accident categories and selected accidents

| Accidents in catagory[a] | Quantity released (kg) | Duration (min) | No deaths downwind distance[b] (km) |
|---|---|---|---|
| **VX Class V** | | | |
| SL 26, SL 5, SL 4, SL 15 | 7,560 to 34,100 | 20 to 360 | 29 to 57 |
| **VX Class IV** | | | |
| SL 15, SL 16 | 560 to 920 | 30 to 240 | 9 to 11 |
| **VX Class III** | | | |
| VO4, PO 29, PO 13, SL 4, PO 33 | 90 to 380 | 20 to 360 | 2 to 8 |
| **VX Class II** | | | |
| VO 4, HF 3, PO 29, PO 33 | 15 to 80 | 20 to 360 | 2 to 4 |
| **VX Class I** | | | |
| HF 11, HO 12, HS 5, PO 49, PO 52, HF 13 | 3 to 10 | 0 to 60 | 1 |

[a]The first accident listed in each class has the largest quantity released and is selected to represent the category.

[b]No-death distance is the length of the plume contour at which the expected concentration is less than the lethal concentration for adult males (i.e., 2 mg/m$^3$), given that 3-m/s winds and D stability prevail. Stability classes are used to represent the extent of atmospheric turbulence at the location at the time of the accident. Several widely used classification schemes are available. The most widely used scheme was originally proposed by Pasquill (1961), for diffusion from low-level, nonbuoyant sources over open country. The categories of stability class are: (A) extremely unstable conditions, (B) moderately unstable conditions, (C) slightly unstable conditions, (D) neutral conditions, (D) slightly stable conditions, (E) moderately stable conditions, and (F) extremely stable conditions. Gifford (1976) examines modifications to Pasquill's scheme to account for elevated and buoyant releases, boundary-layer stability, and diffusion over great distances.

#### 4.1.1.3 H/HD Accidents

For agent H/HD, the potential accidents are partitioned into five classes of accidents (see Table 4.4). Again, the quantity released is the determining factor in the classification of each accident. Fortunately, the smallest class of accidents is not expected to reach the installation boundaries and thereby is not considered.

The H/HD Class V accidents are the result of external events and are expected to release between 269,000 and 550,000 lbs (122,300 to 245,200 kg) of H/HD. Such catastrophic releases are the result of external events lasting 30 to 360 min and have a no-deaths downwind distance of 20 to 31 km under 3-m/s winds. The results could impact human populations more than 100 km from the release point under more stable meteorological conditions. This category of accidents is represented by fire in a warehouse caused by an earthquake, SL 28, which is the largest amount of agent released by any accident involving H/HD.

The H/HD Class IV accidents also result from aircraft crashes that release from approximately 19,900 to 68,000 lbs (9,050 to 30,900 kg) of agent H/HD. Accidents in this category last from 20 to 600 min and potentially effect people between 7 and 12 km under 3-m/s winds, with potential impacts reaching about 85 km. This class of accidents is represented by a large airplane crash in the storage area (SL 5) which is the accident in the category with largest release of agent.

The H/HD Class III accidents include both internal and external initiating events and are expected to range in amount of agent released from approximately 1300 to more than 8,000 lbs (630 to 3,820 kg). Accidents in this category occur over a 20-min to 5-h period, have no-deaths downwind distances from 2 to 4 km under 3-m/s winds, and could impact people as far away as 25 km. This category of accidents is represented by the Class III accident with the largest quantity of H/HD released, SL 4.

H/HD Class II accidents include both internal and external initiating events and are expected to range in amount of agent release from approximately 85 to 511 lbs (40 to 230 kg). Accidents in this category are of 10 to 360 min in duration, have associated no-deaths downwind distances of about 1 km under 3-m/s winds, and could result in fatalities out to approximately 4 km under stable meteorological conditions. This category of accidents is represented by an earthquake damaging the disposal facility (PO 29) which is the potential accident within the category with the largest amount of H/HD released.

No H/HD Class I accidents result in estimated no-deaths downwind distances exceeding the post boundaries under any meteorological conditions.

### 4.1.2 Downwind Proximity

The protective actions to be implemented and their effectiveness will depend in part on the location of individuals relative to the accident site. Although protective actions conceivably could vary continuously with distance from the accident site, this is not a reasonable or practical approach (Carnes et al. 1989a through 1989h). Rather, protective actions likely will vary according to whether the individual is within an immediate response zone (IRZ) or protective action zone (PAZ).

**Table 4.4. H/HD accident categories and selected accidents**

| Accidents in catagory[a] | Quantity released (kg) | Duration (min) | No deaths downwind distance[b] (km) |
|---|---|---|---|
| **H Class V** | | | |
| SL 28, SL 5, SL 4, SL 15 | 122,300 to 245,200 | 30 to 360 | 23 to 31 |
| **H Class IV** | | | |
| SL 5, SL 4 | 9,050 to 30,900 | 20 to 60 | 7 to 12 |
| **H Class III** | | | |
| SL 4, SL 5, PO 13, SL 16 | 630 to 3,820 | 20 to 240 | 2 to 4 |
| **H Class II** | | | |
| PO 29, VO 4, HF 3 PO 13, PO 33 | 60 to 230 | 10 to 360 | 1 |
| **H Class I** | | | |
| None[c] | 8 to 20 | 10 to 240 | <1 |

[a]The first accident listed in each class has the largest quantity released and is selected to represent the category.

[b]No-death distance is the length of the plume contour at which the expected concentration is less than the lethal concentration for adult males (i.e., 100 mg/m$^3$), given that 3-m/s winds and D stability prevail. Stability classes are used to represent the extent of atmospheric turbulence at the location at the time of the accident. Several widely used classification schemes are available. The most widely used scheme was originally proposed by Pasquill (1961), for diffusion from low-level, nonbuoyant sources over open country. The categories of stability class are: (A) extremely unstable conditions, (B) moderately unstable conditions, (C) slightly unstable conditions, (D) neutral conditions, (E) slightly stable conditions, (F) moderately stable conditions, and (G) extremely stable conditions. Gifford (1976) examines modifications to Pasquill's scheme to account for elevated and buoyant releases, boundary-layer stability, and diffusion over great distances.

[c]No potential accidents in this category are likely to exceed post boundaries.

For preliminary evaluation, distances of 3, 10, and 20 km from the accident site were selected to represent the inner IRZ, the outer IRZ, and midpoint in the PAZ, respectively. As noted in Carnes et al. 1989a though 1989h, the recommended IRZ distances are 10 km for APG, LBAD, NAAP, PUDA, and UMDA and 15 km for ANAD, PBA, and TEAD. The recommended PAZ distances are 50 km for PBA and UMDA, 35 km for ANAD, 30 km for UMDA, 25 km for APG, LBAD, and NAAP, and 15 km for PUDA.

Estimating exposure reductions at these distances for various protective actions and accidents modeled provides a general sense of the effectiveness of alternative protective actions. As noted in Sect. 3, the model can be run for other distances from the accident site.

### 4.1.3 Meteorological Conditions

Given a specific accident scenario, the time of arrival of the toxic plume at a given distance will vary with meteorological conditions. Windspeed, atmospheric stability, and mixing height are all important factors in determining agent concentrations/exposures at given distances (see Sects. 3.2.3 and 3.4.2). Higher windspeeds, obviously, will move the toxic plume to a given distance faster than lower windspeeds; alternatively, for that same accident, a higher windspeed and associated unstable atmospheric conditions will result in more diffusion and lower concentrations/exposures at that point.

Three classes of meteorological conditions are selected to represent the universe of meteorological conditions: (1) rapid windspeeds and unstable atmospheric conditions (6 m/s, C atmospheric stability class, and 500-m mixing height); (2) moderate or average windspeeds and stability (3 m/s, D atmospheric stability class, and 500-m mixing height); and (3) low windspeeds and stable atmospheric conditions (1 m/s, E atmospheric stability class, and 500-m mixing height). Under these conditions, the middle or center of a toxic plume would arrive at 3 km in approximately 8, 17, and 50 min, respectively. The same plume would arrive at 10 km in approximately 28, 56, and 167 min, respectively; for a 20-km distance, the plume would arrive in approximately 56, 111, and 333 min, respectively.

Estimated exposure of unprotected individuals during selected hypothetical accidents for varying distances from the accident site and under varying meteorological conditions are shown in Tables 4.5 through 4.7 for each agent. The exposures are expressed in mg-min/m$^3$, which indicates the cumulative quantities of agent to which an individual may be exposed in the first 3 h of an accidental release. The reader should note that for the slow onset accidents (i.e., 1-m/s windspeeds), it takes approximately 5 $\frac{1}{2}$ h for the plume to traverse 20 km; therefore, an individual at that distance is not expected to receive any exposure during the first 3 h before the agent cloud arrives.

The agent exposures presented in Tables 4.5 through 4.7 indicate that very rapid onset, which would expose people 3 km from the source point in about 8 min, tends to dissipate the concentration of agent. Only the most catastrophic accidents (Class V) present any significant emergency planning challenge under these conditions. Conversely, slow onset, which would reach people located 3-km downwind in just under an hour, fails to dissipate the concentration of agent such that all classes of accidents present significant protection requirements. Fortunately, slow onset also allows more time for emergency

Table 4.5. Unprotected GB exposures[a] (mg-min/m$^3$) for first 3 h, by accident, meteorological conditions, and downwind distance

| Accident class | Scenario code | Downwind distance (km) 3 | 10 | 20 |
|---|---|---|---|---|
| | | **Rapid onset (6-m/s winds, C stability)[b]** | | |
| GB I | HF 11 | 0.1 | 0 | 0 |
| GB II | VO 4 | 0.3 | 0 | 0 |
| GB III | PO 13 | 0.6 | 0.1 | 0 |
| GB IV | SL 16 | 1.8 | 0.2 | 0.1 |
| GB V | SL 4 | 18 | 1.7 | 0.7 |
| | | **Moderate onset (3-m/s winds, D stability)[b]** | | |
| GB I | HF 11 | 0.7 | 0.1 | 0 |
| GB II | VO 4 | 2.6 | 0.2 | 0.1 |
| GB III | PO 13 | 4.9 | 0.4 | 0.1 |
| GB IV | SL 16 | 15 | 1.6 | 0.5 |
| GB V | SL 4 | 180 | 15 | 3.9 |
| | | **Slow onset (1-m/s winds, E stability)[b]** | | |
| GB I | HF 11 | 40 | 7 | 0 |
| GB II | VO 4 | 160 | 25 | 0 |
| GB III | PO 13 | 300 | 40 | 0 |
| GB IV | SL 16 | 1,120 | 190 | 0 |
| GB V | SL 4 | 12,600 | 1,800 | 0 |

[a]Exposure rounded in relationship to human health effects.

[b]Stability classes are used to represent the extent of atmospheric turbulence at the location at the time of the accident. Several widely used classification schemes are available. The most widely used scheme was originally proposed by Pasquill (1961), for diffusion from low-level, nonbuoyant sources over open country. The categories of stability class are: (A) extremely unstable conditions, (B) moderately unstable conditions, (C) slightly unstable conditions, (D) neutral conditions, (E) slightly stable conditions, (F) moderately stable conditions, and (G) extremely stable conditions. Gifford (1976) examines modifications to Pasquill's scheme to account for elevated and buoyant releases, boundary-layer stability, and diffusion over great distances.

Table 4.6. Unprotected VX exposures[a] (mg-min/m$^3$) for first 3 h, by accident, meteorological conditions, and downwind distance

| Accident class | Scenario code | Downwind distance (km) 3 | 10 | 20 |
|---|---|---|---|---|
| | | **Rapid onset (6 m/s winds, C stability)[b]** | | |
| VX I | HF 11 | 0 | 0 | 0 |
| VX II | VOR 4 | 0.3 | 0 | 0 |
| VX III | VOM 4 | 1.4 | 0.1 | 0.1 |
| VX IV | SL 15 | 2.8 | 0.3 | 0.1 |
| VX V | SL 26 | 40 | 4.1 | 1.0 |
| | | **Moderate onset (3 m/s winds, D stability)[b]** | | |
| VX I | HF 11 | 0.4 | 0 | 0 |
| VX II | VOR 4 | 2.7 | 0.2 | 0.1 |
| VX III | VOM 4 | 15 | 1.2 | 0.3 |
| VX IV | SL 15 | 30 | 2.5 | 0.7 |
| VX V | SL 26 | 460 | 40 | 12 |
| | | **Slow onset (1 m/s winds, E stability)[b]** | | |
| VX I | HF 11 | 25 | 4 | 0 |
| VX II | VOR 4 | 170 | 25 | 0 |
| VX III | VOM 4 | 800 | 110 | 0 |
| VX IV | SL 15 | 1,800 | 270 | 0 |
| VX V | SL 26 | 36,000 | 6,100 | 0 |

[a]Exposure rounded in relationship to human health effects.

[b]Stability classes are used to represent the extent of atmospheric turbulence at the location at the time of the accident. Several widely used classification schemes are available. The most widely used scheme was originally proposed by Pasquill (1961), for diffusion from low-level, nonbuoyant sources over open country. The categories of stability class are: (A) extremely unstable conditions, (B) moderately unstable conditions, (C) slightly unstable conditions, (D) neutral conditions, (E) slightly stable conditions, (F) moderately stable conditions, and (G) extremely stable conditions. Gifford (1976) examines modifications to Pasquill's scheme to account for elevated and buoyant releases, boundary-layer stability, and diffusion over great distances.

**Table 4.7. Unprotected H/HD exposures[a] (mg-min/m$^3$) for first 3 h, by accident, meteorological conditions, and downwind distance**

| Accident class | Scenario code | Downwind distance (km) 3 | 10 | 20 |
|---|---|---|---|---|
| | | **Rapid onset (6 m/s winds, C stability)[b]** | | |
| H/HD I | PO 29 | 3 | <1 | <1 |
| H/HD II | SL 4 | 5 | <1 | <1 |
| H/HD III | SL 5 | 290 | 40 | 20 |
| H/HD IV | SL 28 | 2,100 | 260 | 130 |
| | | **Moderate onset (3 m/s winds, D stability)[b]** | | |
| H/HD I | PO 29 | 25 | 3 | <1 |
| H/HD II | SL 4 | 50 | 6 | 2 |
| H/HD III | SL 5 | 2,700 | 330 | 110 |
| H/HD IV | SL 28 | 20,200 | 2,450 | 800 |
| | | **Slow onset (1 m/s winds, E stability)[b]** | | |
| H/HD I | PO 29 | 880 | 160 | 0 |
| H/HD II | SL 4 | 1,890 | 330 | 0 |
| H/HD III | SL 5 | 574,600 | 20,400 | 0 |
| H/HD IV | SL 28 | 921,000 | 160,000 | 0 |

[a]Exposure rounded in relationship to human health effects.

[b]Stability classes are used to represent the extent of atmospheric turbulence at the location at the time of the accident. Several widely used classification schemes are available. The most widely used scheme was originally proposed by Pasquill (1961), for diffusion from low-level, nonbuoyant sources over open country. The categories of stability class are: (A) extremely unstable conditions, (B) moderately unstable conditions, (C) slightly unstable conditions, (D) neutral conditions, (E) slightly stable conditions, (F) moderately stable conditions, and (F) extremely stable conditions. Gifford (1976) examines modifications to Pasquill's scheme to account for elevated and buoyant releases, boundary-layer stability, and diffusion over great distances.

response. Moderate windspeeds of about 3 m/s result in fairly rapid onset of hazard, exposing people at 3 km in about 15 min to significant concentrations.

Figures 4.1 through 4.3 present exposure accumulation in an unprotected environment at 3 km under 3 m/s winds for agent GB, VX, and H/HD, respectively. Only the most catastrophic accidents (Class V) even approach the $LCt_{50}$ for adult males, for each agent except mustard, where the Class IV accident also exceeds the $LCt_{50}$ for adult males. One preliminary conclusion in this regard is that, for noncatastrophic accidents, moderate to fast windspeeds will disperse released agent sufficiently to significantly reduce the need for protection required via emergency response. Figures 4.4 and 4.5 present the estimated GB exposure in an unprotected area at 3 km under 1-m/s and 6-m/s winds, respectively. Figure 4.4 clearly indicates that slower windspeeds increase both the amount of time available to respond and the concentrations of agent likely to reach a given downwind distance. Under 1-m/s winds, the survival of people in close proximity for all classes of accidents will require effective emergency response. At the other extreme, Fig. 4.5 indicates that under 6-m/s winds, the released agent will be sufficiently dispersed so that survival is likely even without emergency response under all except the most catastrophic accidents. However, some adverse effects could be noted.

### 4.1.4 Simplifying Assumptions

A number of additional simplifying assumptions have been made in running the model. These include (1) the time of day of an accident; (2) the warning system used; (3) the amount of time required to detect, assess, and decide to warn the public; and (4) the toxicological end points.

As noted in Sect. 3.2.1, although accidents can occur at virtually any time during the day, they are more likely to occur at certain times. Thus, while the model is capable of being run for virtually any time, the most likely time (about 11:00 a.m.) has been selected for the initial model runs (see Fig. 3.2).

There are also many different warning systems that could be assumed in running the model (see Sect. 3.3.2). For these initial model runs, we have selected a dual indoor/outdoor system: telephone ring-down for indoor and sirens for outdoor. The time it takes to detect an accident, assess it, and decide to warn the public with protective action recommendations likewise can assume a rather wide range. As noted in Sect. 3.3.4, the Confluence, Pennsylvania data appear to be the most appropriate for the CSDP emergency planning and preparedness program; it could be assumed that the CSDP will do 25% better. For initial evaluation, decisions to warn (i.e., encompassing all of the above activities) are assumed to occur in 5 min. Note that the site-specific concept plans (Carnes et al. 1989a through 1989h) have recommended 5- or 10-min warning times for the CSDP installations.

Finally, it is possible to consider a wide range of acute toxicological responses to chemical agent exposure, including "no effect," "observable effect," "reversible effects," and death for several age and gender classes. Estimates of exposures required to achieve each of these end points are largely derived as extrapolations from laboratory animal data (see Sect. 3.2.4 and Table 3.3). The range of acute effects of interest is effectively bounded by threshold (observable) responses and fatalities ($LCt_{50}$, a reasonable approximation) in

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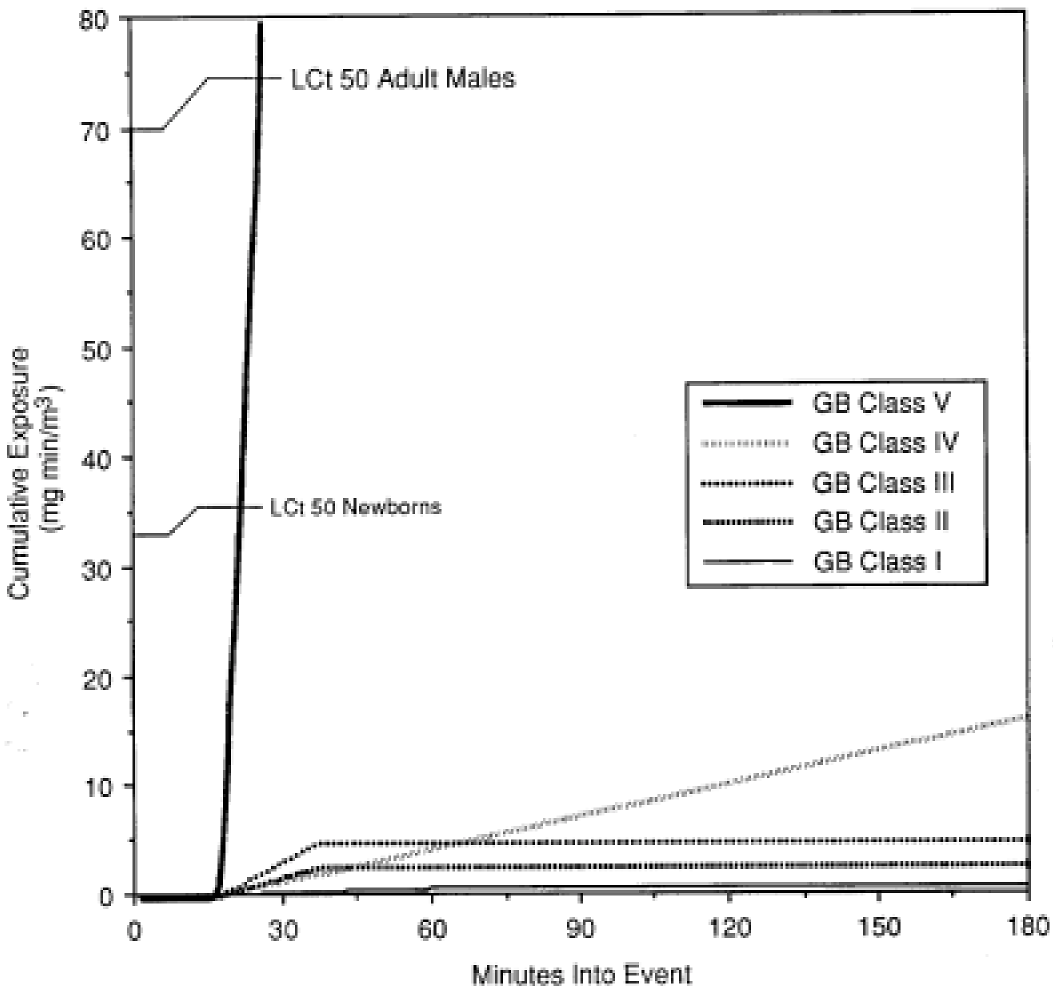


**Fig. 4.1. Expected cumulative exposure to GB without protection at 3 km for selected accidents when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population.

ORNL-DWG 90M-5846

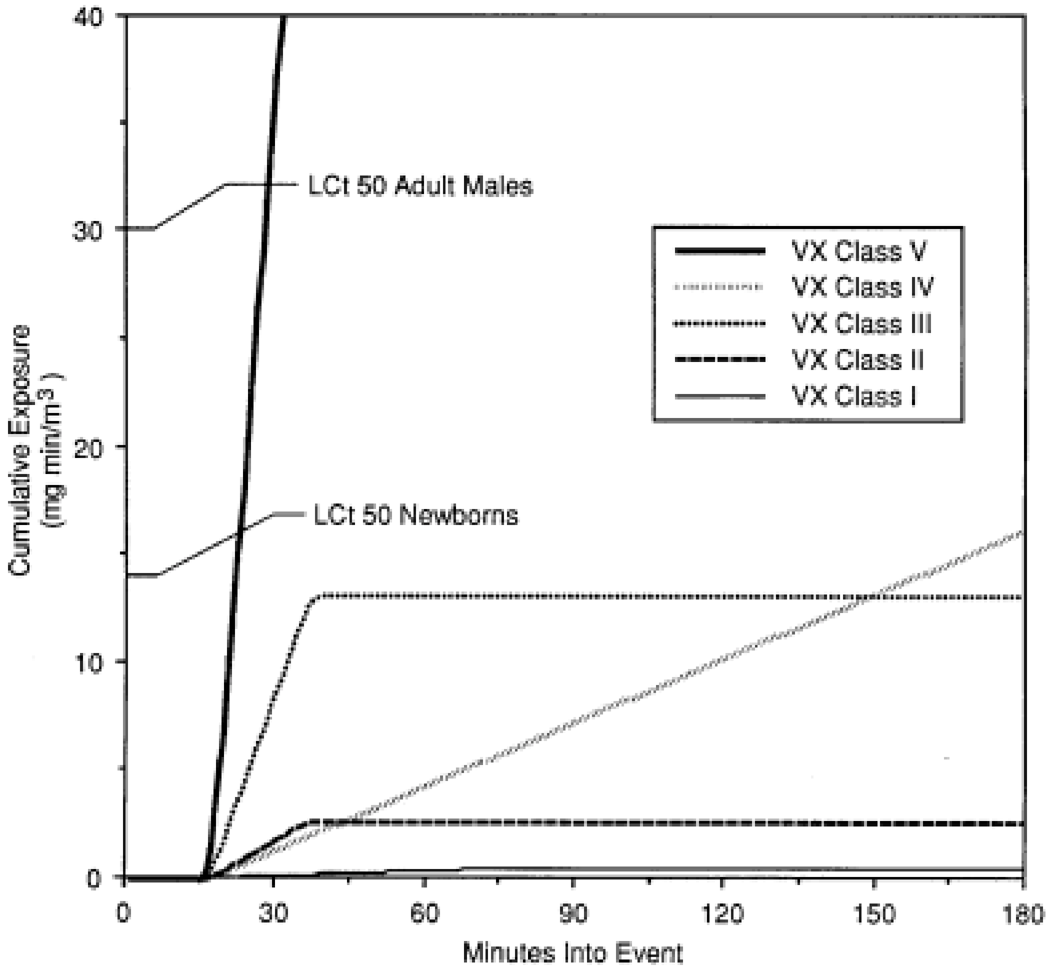


**Fig. 4.2. Expected cumulative exposure to VX without protection at 3 km for selected accidents when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration–time integral, lethal for 50% of reference population.

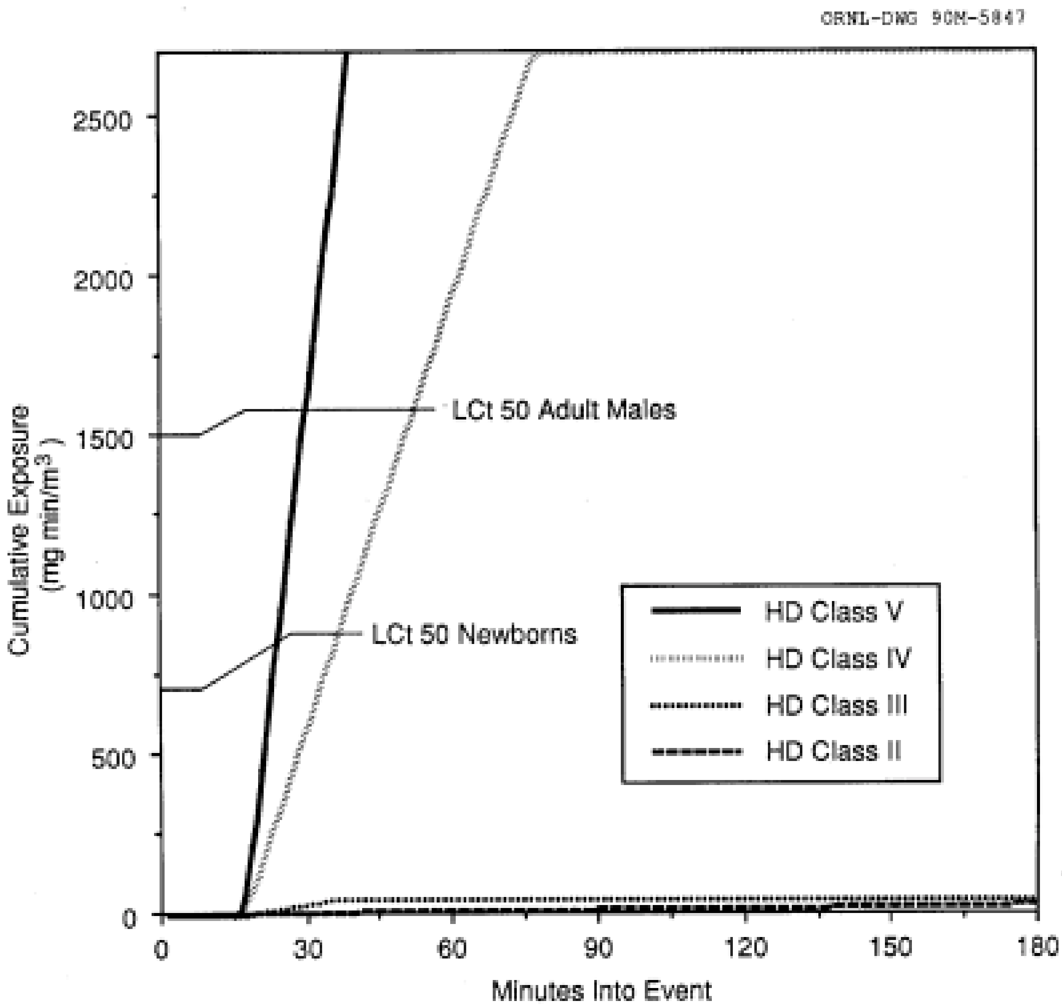


**Fig. 4.3. Expected cumulative exposure to H/HD without protection at 3 km for selected accidents when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration–time integral, lethal for 50% of reference population.

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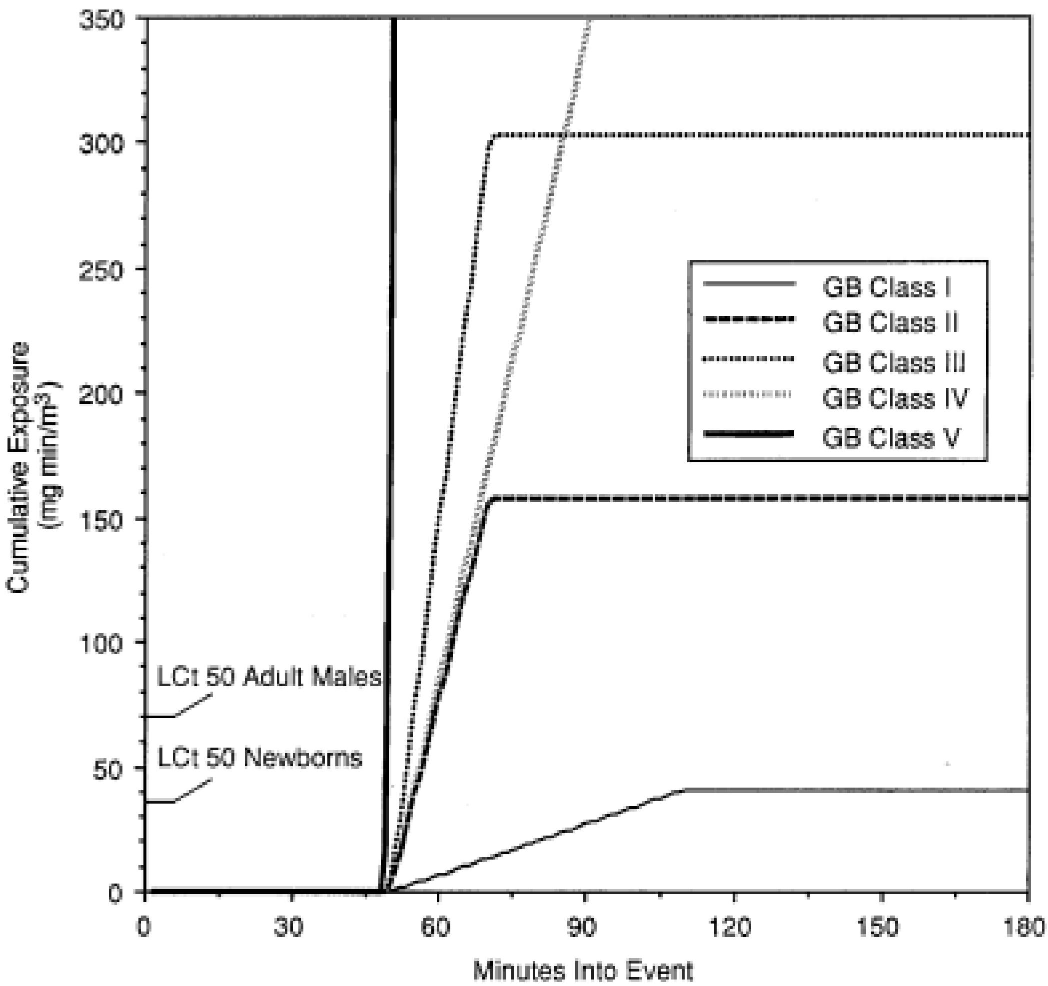


**Fig. 4.4. Expected cumulative exposure to GB without protection at 3 km for selected accidents when 1-m/s winds prevail.** Note that $LCt_{50}$ equals concentration–time integral, lethal for 50% of reference population.

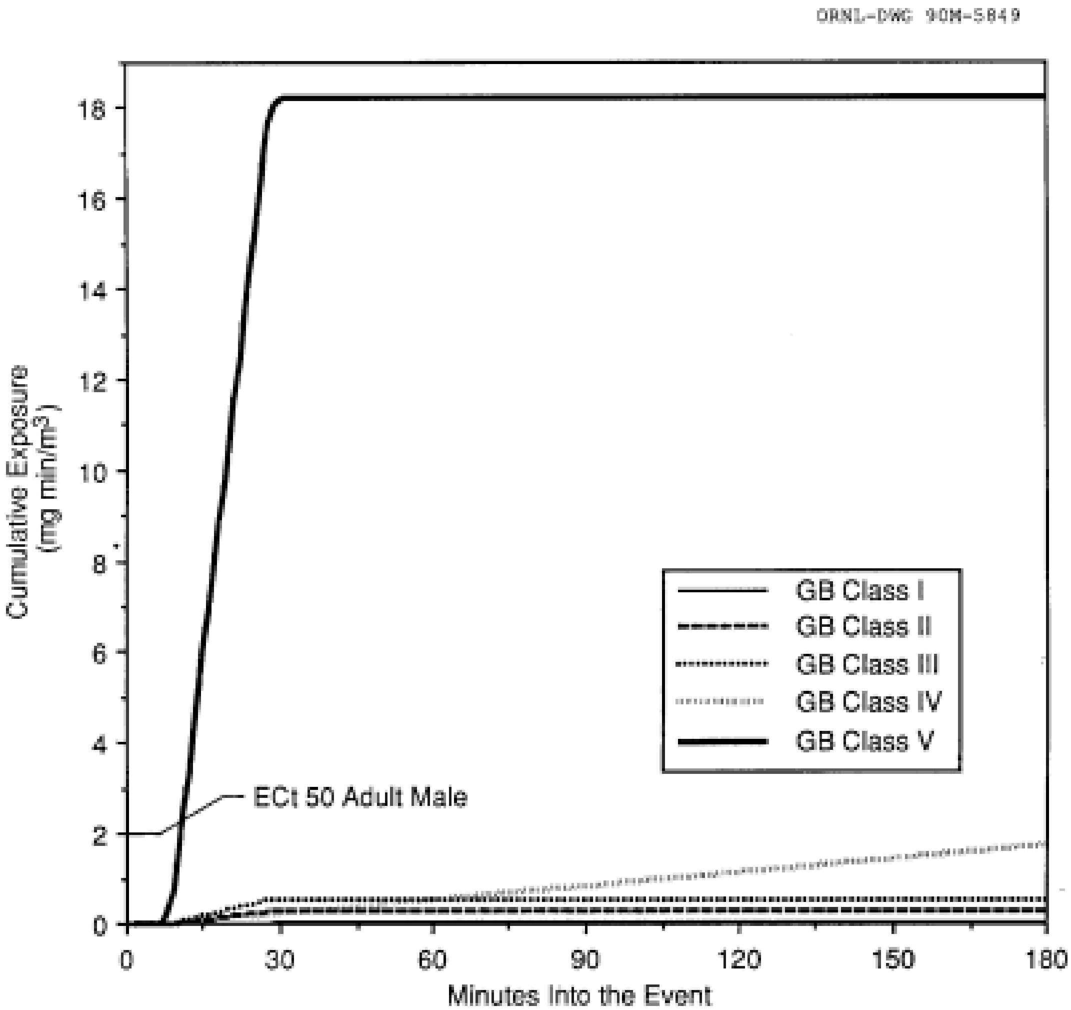


**Fig. 4.5. Expected cumulative exposure to GB without protection at 3 km for selected accidents when 6-m/s winds prevail.** Note that $ECt_{50}$ equals concentration–time integral where 50% of reference population are expected to exhibit observed effects.

adult males and infants. These end points have thus been selected to represent the range of acute toxicological response for this initial evaluation.

## 4.2 ESTIMATING EFFECTIVENESS

### 4.2.1 Calculating Protection Capacity

One of the principal concerns of this research involves the physical ability of various protective actions to reduce exposure to chemical agents. Protection capacity assumes that all behavioral or response functions are adequately performed to ensure design criteria performance of protective measures. Protection capacity, therefore, does not take into consideration the proportion of the population or number of people having been warned, deciding to respond, and implementing the specified respiratory device. The protection capacity is the sum of the reduced concentrations from the beginning of the accident to time t, where t is any moment during the accident.

#### 4.2.1.1 Protection Capacity

For a respiratory device the ability to reduce exposure is a simple function of leakage around the device and penetration through the filter, known as breakthrough. For a respiratory device characterized by leakage, L, and breakthrough, B, the protection capacity is calculated as a direct function of L and B, and the concentration of agent, in the unprotected environment. For any moment, t, the protection capacity of a respiratory device is expressed as the expected concentration while using a given respiratory device,

$$C_p = (1 - b)\, C_u\, L + b\, C_u ,$$

where $C_u$ is the concentration of chemical in the unprotected environment at t, L is leakage, and b is equal to 1 if the sum of $C_u$ exceeds the breakthrough standard B at time t; otherwise b is 0. The first part of the binomial represents the leakage prior to reaching the breakthrough standard, and the second part of the binomial accumulates the entire unprotected concentration once the breakthrough standard is reached.

For in-place shelters, the ability to reduce exposure depends on the amount of infiltration from the unprotected environment to the protected environment, and the difference in concentration between the protected and unprotected environments (Chester 1988). For any moment, t, the protection capacity of an in-place shelter is expressed as the expected concentration in the protected environment,

$$C_{pt} = C_{pt-1} + I\,(C_{ut-1} - C_{pt-1}) ,$$

where $C_p$ and $C_u$ are as previously defined, I is the infiltration rate in period t, and $C_p$ is the amount of agent in the protected environment at the beginning of the period. This formulation allows for the mixing of fresh (noncontaminated) air into the protected environment as the plume passes by and $C_u$ becomes smaller than $C_p$ at the same rate at which it became contaminated as the plume arrived.

For evacuation, the reduced concentrations are a simple function of the proportion of the population completing evacuation and the concentration of agent in the unprotected environment. The protection capacity associated with evacuation for any moment t is expressed as the expected concentration given the probability of completing the evacuation at time t,

$$C_p = (1 - P(e))\, C_u ,$$

where $C_u$ is the unprotected concentration and P(e) is the probability of completing evacuation. Unfortunately, the completion of evacuation is not completely separable into the physical or structural aspects and the behavioral or response elements. While evacuation time is clearly a function of driving behavior, it is also a function of structure (e.g., carrying capacity of roads, maximum attainable speeds of vehicles). In theory, if all road networks were large enough to handle all evacuation traffic, then exposure reduction capacity for evacuation would be complete (i.e., no exposure would be received); however, because the times at which evacuations can be completed are both structural and behavioral, the exposure reduction capacity for evacuation can exceed zero. The protection capacity may also be expressed in terms of exposure at time t as

$$Ct_p = \sum C_p t .$$

#### 4.2.1.2 Response-Adjusted Exposure

To reflect accurately the effectiveness of a protective action, the measure must reflect the probability of implementing the action. Expected exposure for a given population at time t is calculated as

$$E(C_p) = (P(i)\, C_p) + (1 - P(i))\, C_u ,$$

where P(i) is the joint probability of having reached a decision to warn, receiving warning, deciding to respond and implementing that response at time t, and $C_p$ and $C_u$ are the protected and unprotected exposures, respectively. The expected concentration-time integral accumulates the expected concentration $E(C_p)$, from time zero to t, to represent the cumulative exposure, Ct, anticipated for a population protected by protective action i. This expected exposure in the protected environment is a probabilistic measure of population exposure for the given protective action.

### 4.2.2 Model Overview

The protective action support model is conceptually composed of a number of modules that address specific parts of the problem of protective action decision making. Conceptually, the model consists of those modules characterizing the nature of the hazard and its consequences and the modules that characterize emergency response. Each module is linked with the adjacent modules in the process. This is not to say that the

information that each module adds is always equally important to the decision, but rather that each module plays a role in the protective action decision making. An overview of the PAECE is presented in Fig. 4.6 and summarized in Appendix H. PAECE begins with the specification of the initiating events in terms of the time and nature of the accident resulting in a release. The time of the release determines (1) the time at which the emergency response begins, (2) the distribution of people in various locations, and (3) the likelihood of the occurrence of various meteorological conditions. Each module characterizes another step in the emergency response process. The warning diffusion module characterizes warning system effectiveness in terms of the probability of receiving warning at various times in the warning process. The response-decision module characterizes the public's decision to respond to the warning message in terms of public response to previous chemical emergencies. The protective action implementation module characterizes the implementation of various protective actions in terms of probability of completion once the decision to respond is made.

The probability of a completed protective action is the joint probability of having (1) public officials decide to warn, (2) the public receiving the warning, (3) the population at risk deciding to respond, and (4) the implementation of the protective measure. Such a joint probability must account for the period of time at which the previous step is achieved. For example, if warning is received at minute three, the probability of response is potentially greater than zero, but up to that point the probability was structurally zero. The joint probability of two probability distributions that are related in this manner cannot be calculated as if they had independent probabilities. Consider the joint probability of warning and response at time t in the emergency response process. The joint probability of warning and response at the end of the first moment in time t, $P^{wr}_1$, is equal to the product of the independent probabilities during the period

$$P^{wr}_1 = P^{w}_1 \, P^{r}_1,$$

where $P^{w}_1$ is the probability of warning in the first period after the decision to warn and $P^{r}_1$ is the probability of responding in the first period following the receipt of warning. In the second period of time, the joint probability of warning and response is

$$P^{wr}_2 = P^{w}_2 \, P^{r}_1 + P^{w}_1 \, P^{r}_2 + P^{wr}_1 ,$$

that is, the probability of being warned in period 2 and responding in the first period of response plus the probability of being warned in period 1 and responding in the second period of response plus the joint probability from the previous period. It can then be seen that the third period joint probability is

$$P^{wr}_3 = (P^{w}_3 \, P^{r}_1) + (P^{w}_2 \, P^{r}_2) + (P^{w}_1 \, P^{r}_3) + P^{wr}_2 ,$$

that is as each segment of the population, as it receives the warning message, responds in the first period thereafter with probability $P^{r}_1$ and in the second period thereafter with

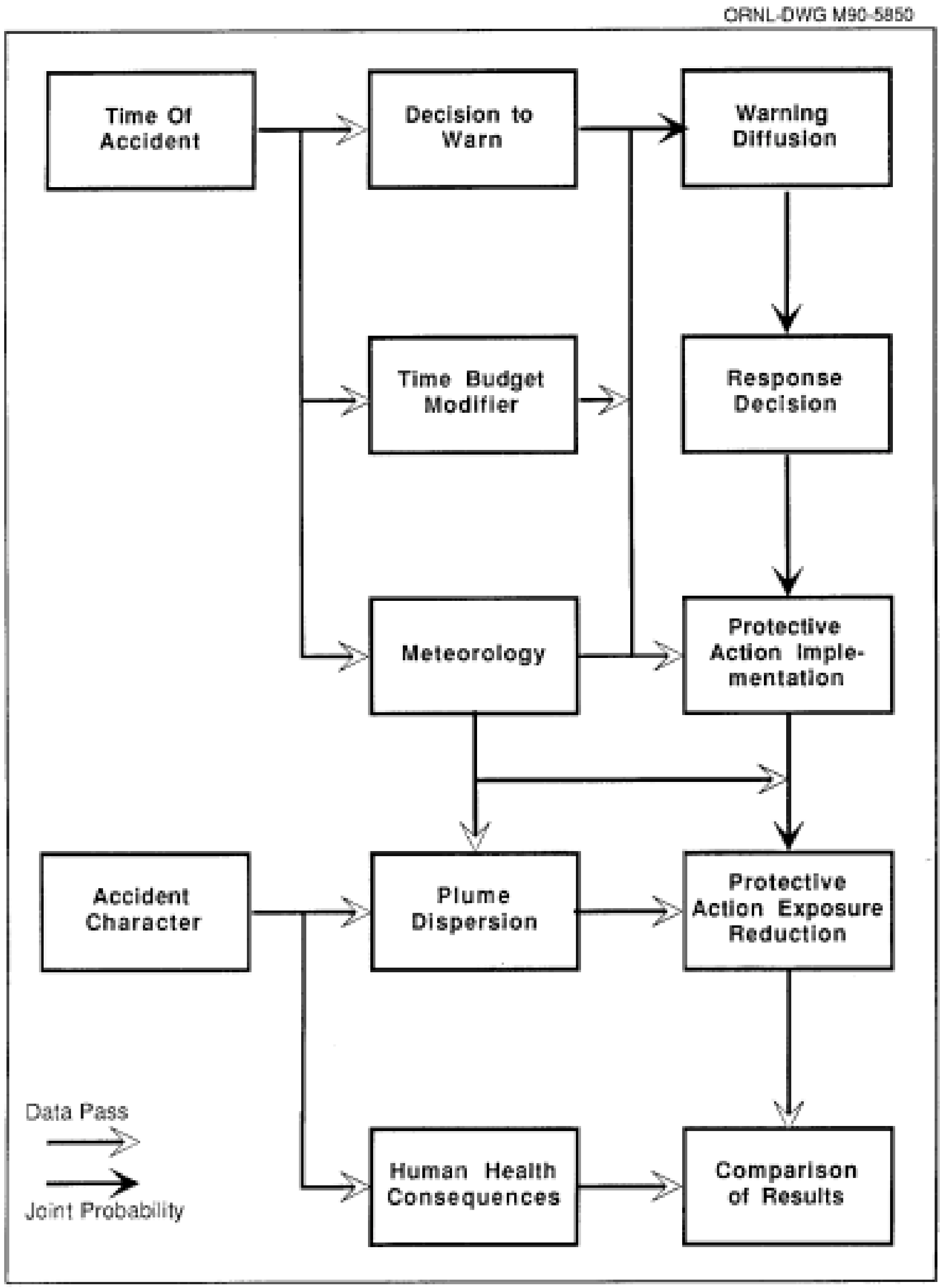


**Fig. 4.6. Conceptual model of protective action evaluation for chemical accidents.**

probability $P^r_2$, with each subsequent step augmenting the period of response. The general form then is

$$p^{wr}_t = p^{wr}_{t-1} + \sum_{i=1}^{t} \sum_{j=t}^{1} \left( p^w_i p^r_j \right) ,$$

where the probability of warning at time t into the warning process, $P^w_i$, and the probability of response to that warning once it is received, $P^r_j$, are dependent and lagged in time.

This general formula can be used iteratively. On the first iteration, the probability of the decision to warn and warning receipt are processed to form a joint probability of a decision-to-warn and warning receipt. On the second iteration, the joint probability of a decision-to-warn and warning receipt and the probability of response produce the joint probability of reaching a decision to warn, receiving it, and responding to the warning message. Finally, using that joint probability with the probability of completing implementation of the protective action the joint probability of implementing the selected action is estimated for each time period, t.

Accident characterization, particularly the type and amount of agent released together with the meteorological characterization, allows the estimation of plume dispersion for given downwind distances. These data alone determine concentrations of agent in the unprotected environment. In addition, the type of agent allows selection of the appropriate anticipated human health impacts for comparison with the estimated unprotected and protected exposures.

### 4.2.3 Protective Action Effectiveness

Because of the uncertainty associated with the estimation of various aspects of the model, the qualitative effectiveness of various protective actions is appropriately represented graphically. This achieves two important goals: (1) it places the emphasis on the overall pattern, and (2) it prevents overemphasis on precisely calculated numbers. Two forms of effectiveness are needed to compare various scenarios: (1) to compare various protective actions within the same basic category; and (2) to compare protective actions across categories.

#### 4.2.3.1 Relative Effectiveness

Relative effectiveness is required to compare various protective action alternatives within the evacuation, in-place shelter or respiratory protection category. It is principally used to compare response alternatives for a specified protective measure under various accident and response scenarios. For any moment in the emergency, t, the relative exposure reduction measures the difference between the protection capacity, $C_p$, and the expected exposure, $E(C_p)$. One way to characterize protective action options within asingle category is to calculate the relative exposure reduction (RER) at each time, t:

$$RER = 1 - ( E(C_p) - C_p) / (C_u - C_p) .$$

Averaging RER over the length at the plume allows the direct comparison of the exposure reduction achieved and the maximum reduction possible for the specified protective measure during the plume's passage.

#### 4.2.3.2 Overall Effectiveness

Overall effectiveness is required to compare protective action alternatives that are fundamentally different. At any moment in time, t, the overall exposure reduction measures the difference between receiving no exposure and the concentration reduction, $R^{c}_{t}$. One way to characterize the overall protection afforded by a protective action alternative is to calculate the overall exposure reduction (OER) at each time, t:

$$OER_t = 1 - E(C_p) / C_u .$$

Averaging OER over the length of the plume allows the direct comparison of the exposure reduction achieved via various alternatives with perfect protection leading to zero exposure during the plume's passage.

### 4.3 Limits, Uncertainty, and Interpretation

The methodology employed herein involves mathematical simulation. Use of a simulation model of the accident, its consequences, and the emergency system used to respond to the accident to compare the degree of protection afforded by various protective measures is a suitable way to evaluate effectiveness of protective action alternatives. However, there are limits to the utility of the method in determining the number of lives saved or the expected value of various protective actions alternative.

One key limitation involves the stochastic nature of the estimated expected exposure. Because PAECE uses a stochastic estimate of the joint probability of reaching a decision to warn, receiving a warning, deciding to respond, and implementing the protective action, it may be interpreted as an expected value. People who implement the protective action early would have lower exposures than the expected value, and people who implement protective measures late would receive exposures greater than expected. Hence, the expected exposure is in a sense an average or typical exposure given the distribution of warning, response, and implementation times from the beginning of the event. Depending on the distribution itself, people who implement the protective measure either before the release or early into the release are more likely to achieve protection near the capacity of that protective action—the exposure reduction capacity. On the other end of the distribution, people who implement the protective action late in the sequence are more likely to receive exposures similar to the unprotected exposure. Hence, the results of these analyses are interpreted as a distribution of results with an expected value estimate of the "middle" of that distribution rather than as a deterministic value that represents absolute exposure levels or exposure limits.

Perhaps a more important implication of this general limitation on the interpretation of expected exposure results concerns the absolute exposure and the exposure reduction achieved. It is possible to get results that indicate that a particular protective action

drastically reduces the expected exposure when compared with the unprotected exposure (e.g., 90 or 95% reductions), but with the absolute exposure remaining well above the $LCt_{50}$ for adult males. Such a case indicates that even though vast exposure reductions can be achieved, protection is limited. The converse is also true; even though the results indicate that given the particular protective measure, the expected exposure remains below the $LCt_{50}$ for infants, this cannot be interpreted to mean no deaths will occur. In fact, some people may not survive (e.g., people who implement late, sensitive people, people who implement the action improperly, people caught in pockets of accumulated agent).

Finally, uncertainty permeates the PAECE at every juncture: the dispersion model at best predicts the expected exposure within ±50%; the decision-to-warn assumptions are based on limited cases; the receipt of warning is based on extrapolations and interpolations of limited data; public response is estimated based on a limited number of previous chemical accidents; and implementation of in-place shelter techniques is based on a limited number of trials. Although any one of these uncertainties may be estimated, the combined effect of these uncertainties cannot be estimated. Any particular numerical result of the model is sensitive to these uncertainties; however, the relative effectiveness of various protective actions is not affected by either the individual uncertainties or the combined uncertainty. Moreover, the greater the difference in effectiveness between one protective action and another, the more likely that the relative effectiveness is in the predicted direction. These uncertainties do not reduce the effectiveness of the model as a way of systematically comparing protective action alternatives but must be recognized to avoid over interpreting the results.

# 5. EVACUATION FOR CHEMICAL AGENT EMERGENCIES

This section describes the analysis of evacuation as a protective measure that avoids exposure. This section first considers the concept of evacuation in terms of constraints associated with evacuation, which completes the model development; then, it will continue with the preliminary analysis in terms of a screening analysis and a closer examination of selected scenarios. The section ends with some preliminary conclusions concerning the use of evacuation to avoid exposure in chemical agent emergencies.

## 5.1 EVACUATION CONCEPTS

Evacuation is the collective mass movement of people and property away from a source of potential threat of injury, death, or damage and the return after the threat dissipates. As defined, evacuation is not a stimulus-response type of behavior. It is viewed as a process by which people form images of threat or risk and come to act upon the available information in setting a course of action or inaction. Evacuation is also used here to describe movements of significant groups of people. While it is inappropriate to define a precise threshold of how many people must leave to constitute a collective movement, it is clear that evacuation is not a person escaping from a burning car, or that a person taking evasive action from an aggressive person is not it (Wenger 1985). As defined, evacuations are round-trip events. They involve movement away from and movement back to the area at risk. This latter facet is frequently overlooked or not emphasized in the conceptualization of evacuation research.

Evacuations are sometimes distinguished as to whether they are precautionary or reactive. Precautionary evacuations are defined as those in which people move away from a potential threat but the threat fails to materialize. Reactive evacuations are defined as those in which people move away from an occurring hazard. This distinction is somewhat artificial in that both types are conducted to protect the public. In the former, a postanalysis shows that it was not needed. Often what starts as a precautionary evacuation becomes reactive when the potential event occurs.

Evacuations rarely are carried out forcefully or by police order. Most evacuations involve some degree of human judgment in which the public exercises some freedom of choice. The degree to which public officials and emergency or law enforcement personnel impose a sense of force may range from mild recommendations to forceful removal. The norm is somewhere in between. Policies and laws on this matter, as well as who has the authority to recommend an evacuation, vary according to state and community.

Evacuations are both temporal, and spatial. Some evacuations, such as for hazardous material incidents or volcanic eruptions, may turn into an extended evacuation or a semipermanent relocation. Ultimately, this may lead to permanent migration. The exact time threshold between evacuation and permanent population migration, however, has not been defined.

Drabek and Stephenson (1971) identified four types of evacuations: (1) An evacuation by invitation occurs when someone outside the area at risk provides the means or impetus for someone at risk to leave. (2) Evacuation by decision or choice involves individual processing of warning information to arrive at a decision to leave and then take

action. (3) Evacuation by default involves behavior dictated by actions other than by seeking safety from the hazardous event. (4) Evacuation by compromise is characterized by people following orders even though they do not desire to leave.

Perry (1985) differentiates four types of evacuation using the concepts of the timing of the movement and the length of the stay. Four types of evacuation are identified by categorizing, timing as either preimpact or postimpact, and length of stay as either short-term or long term. "Preventive" evacuations are short-term movements before impact. "Protective" evacuations are preimpact movements over a long-term time frame. "Rescue" evacuations are short-term movements of people out of the impact zone immediately after the impact. "Reconstructive" evacuations are the long-term movements that occur after the impact period. Perry also distinguishes among voluntary and coercive evacuation.

Evacuations involve a series of organizational and individual or family decisions. At the organizational level, the following decisions are frequently made in most potential evacuation situations:

1. whether to notify,
2. whether to evacuate,
3. areas to evacuate,
4. when to issue warning,
5. via what channel to communicate,
6. what nature of recommendations and instructions,
7. content of evacuation notifications, and
8. when to return.

At the individual or family level, comparable types of decisions include:

1. whether to evacuate,
2. when to evacuate,
3. what to take,
4. how to travel,
5. route of travel,
6. where to go, and
7. when to return.

The nature of these decisions help illustrate that evacuation is a complex social process and not a stimulus-response event. While these decisions are being made, considerable communication and social interactions occur. As a result, evacuation planning is not a perfect science and at times is a highly politicized topic.

### 5.1.1 Warning Compliance

Evacuation rates are defined as the percentage of the population at risk that evacuates. The definition of the population at risk, however, is fairly subjective. Alternative definitions are the areas ordered or advised to evacuate, the areas that receive

some impact from the hazard, or the areas in which people think they are at risk based on the warning information. In this analysis, the defacto definition is the sample population included in the warning response study by the original researcher. This definition may be misleading depending on assumptions about how the sample was defined and whether or not it is representative of the true population at risk. Insufficient information exists to make judgments about such problems.

Taking existing evacuation research data at face value, evacuation rates range from 32 to 98% of the estimated population at risk. This suggests that the evacuation rate is probably meaningless for many evacuation settings. Obviously, this rate is not a complete measure of evacuation success. A better measure would be the injury and fatality rates among the nonevacuees, but this statistic is rarely collected because it is difficult to measure.

In comparing warning rates with evacuation rates, an interesting pattern emerges. In only one of the cases observed did a greater percentage of people evacuate than were warned. In the remaining cases more were warned than left. This suggests that, to achieve a high rate of evacuation when it is prudent due to the risks involved, a high level of warning is needed. This underscores the importance of warning systems to support evacuation planning.

Evacuation rates also can be examined under conditions of perceived or objective risk. Figure 5.1 provides estimates of the evacuation rates at high vs low risk. The risk being measured is the level of perceived risk. Indifference to risk is represented by the line bisecting the graph at a 45_ angle. Evacuation rates were insensitive to risk in only one of the cases observed. In the other cases, evacuation rates under conditions of perceived high risk ranged from less than 40% to 100%. In the two chemical accidents studied, the evacuation compliance was 100% in the high-risk group. The ratio of high to low risk averaged about 2.5 to 1, although in some cases it was as high as 5 to 1. Similar findings occur when risks are defined using some objective scale. For several recent hurricanes, Baker (1987) found that around 90 to 95% of people in geographically defined high risk areas evacuated as compared with 25 to 35% from low risk areas.

Fairly limited data suggest that not all people who are defined to be at risk need to evacuate to prevent personal harm. Evacuation rates decrease as level of risk decreases although not always in a direct linear fashion. In high-risk areas, warning systems can achieve a high rate of evacuation (Fig. 5.1). In low-risk areas, evacuation rates are significantly lower. Often, this is because people at lower risk take some other form of protective action, such as sheltering. In low-risk areas, even when an evacuation is ordered, evacuation rates are low. This suggests that the public may be a fairly good appraiser of the microconditions of risk in their environments. Unfortunately, the public is not always correct. Until planning for evacuations can consider risk information at much more detailed levels and provide that information to the public, this process of citizen risk estimation is likely to continue.

In many evacuations, people outside the areas officially ordered to leave typically evacuate as well. They do so for several reasons. They often believe that they are in an area that was told to leave. They may believe that their locations are risky enough in light of the uncertainty of the event, to take some precaution. They may leave because they had friends or relatives who left and they are acting accordingly. They may have

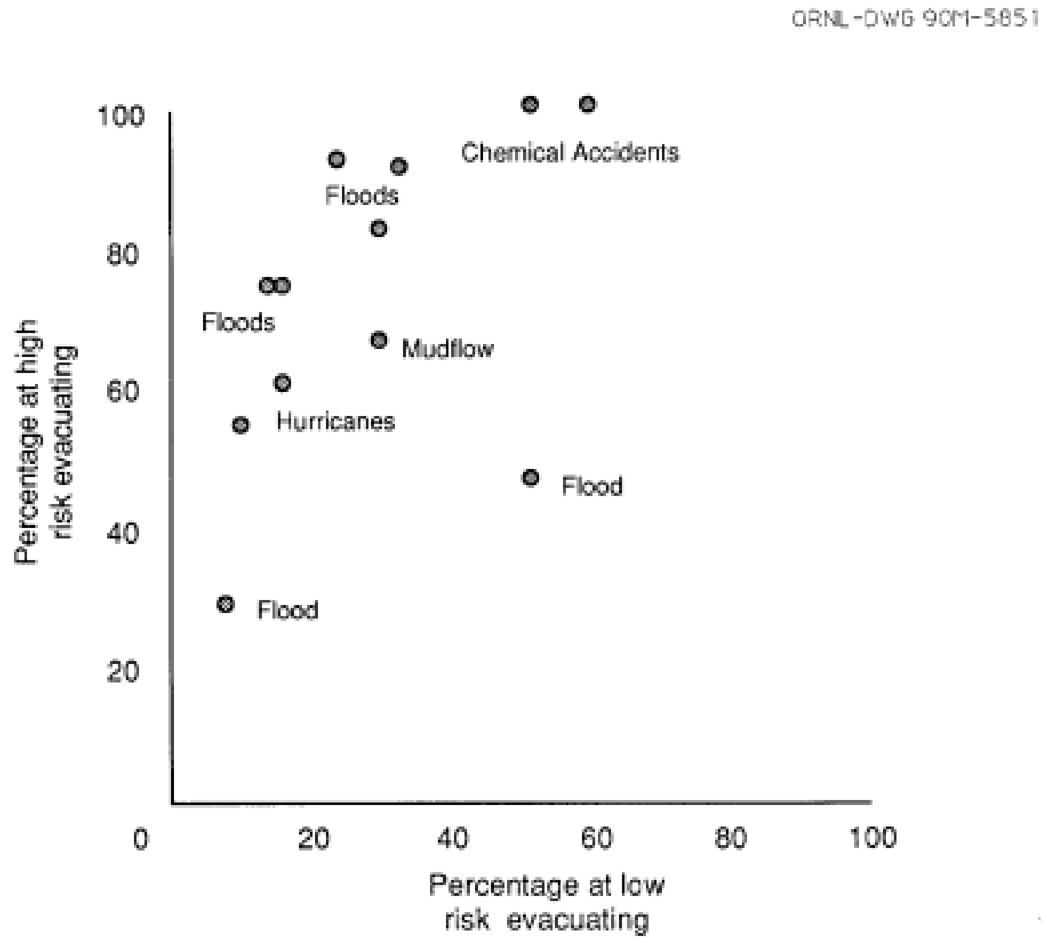


**Fig. 5.1. Effect of risk on evacuation rates.** Data for graph from I. Burton et al., *The Mississauga Evacuation, Final Report*, Institute for Environmental Studies, University of Toronto, Toronto, 1981; R. Perry et al., *Evacuation Planning in Emergency Management*, Lexington Books, Lexington, Mass., 1981; R. Perry and M. Greene, *Citizen Response to Volcanic Eruptions: The Case of Mt. St. Helens*, Irvington Publishers, N.Y., 1983; R. Leik and J. Clark, *Community Response to Natural Hazard Warnings: Final Report*, University of Minnesota, Minneapolis, Minn., 1981; R. Perry and A. Mushkatel, *Disaster Management: Warning Response and Community Relocation*, Quorum Books, Westport, Conn., 1984; R. Perry and A. Mushkatel, *Minority Citizens in Disaster*, University of Georgia Press, Athens, Ga., 1986.

received information from or have been told to evacuate by a nonofficial source. Also, they may have done so to avoid being evacuated at a later point of the emergency as the area at risk expanded.

Research suggests that people want to err on the side of caution. Following the Three Mile Island incident, people were asked if they would leave again in a similar situation and the resulting pattern of responses was very similar to that of the original evacuation (Houts, et al. 1981). Baker (1987) reports that similar rates of evacuation occurred following warnings of three successive hurricanes in the same year in Bay County, Florida. Most people indicated that they would leave again in a similar situation. Evacuation behavior does not appear to be highly influenced by false alarms when the public understands the basis of the original threat, why they were told to leave, and why the expected severity of damage did not materialize.

### 5.1.2 Timing of Evacuation

Data indicate that evacuation mobilization times or departure times basically follow a logistic distribution. Data are available on the timing of trip departures for the Mississauga train accident (Burton et al. 1981), three evacuations due to chemical spills in Pennsylvania (Rogers and Sorensen 1989), several flash floods (Perry et al. 1981), and a few hurricanes (Leik et al. 1981). Figure 5.2 shows normalized mobilization times for the various events. The seriousness of the threat and the urgency of the situation, or the time available to leave before the threat is present, probably influences the steepness of the curve. In situations like Mississauga, almost 90% of the first group of evacuees left within 60 min with nearly 60% departing in 10 min or less. In more protracted situations, the same S-curve pattern occurs but is spread out over a longer time frame. People appear to adjust the rapidity of their evacuation behavior in accordance with the severity and timing of the impending threat. Anecdotal information from other studies indicate that a large number of people at risk will quickly take action in a matter of minutes or seconds to escape a potential threat. In the Big Thompson, Colorado, flood, people evacuated seconds before their homes and cars were swept away by flood waters (Gruntfest 1977). In the Cheyenne, Wyoming, flash flood, people had only minutes to evacuate between the warning and the sudden rise of the creek (Sorensen 1987a). Thus, theoretically, a very severe and sudden emergency, mobilization curves possibly could be even steeper than the one found at Mississauga. In addition, response times are likely to reduced by training and education, making evacuation more effective.

Many officials are concerned with people leaving before an official evacuation order. Little data exist on this subject. Often, it is difficult to determine exactly what constitutes an official order. The data from several hurricane events suggest that, in protracted warning situations, some people initiate action after the first warning and before what is defined as the official warning. The number who leave early seems to range between 20 and 30% (Baker 1987). There are likely some circumstances that impact this level. Early evacuation will most likely occur if an official warning is delayed in what appears to be a potentially threatening situation or if the period of time between the initial and official warning proves to be a convenient time to depart. In events with

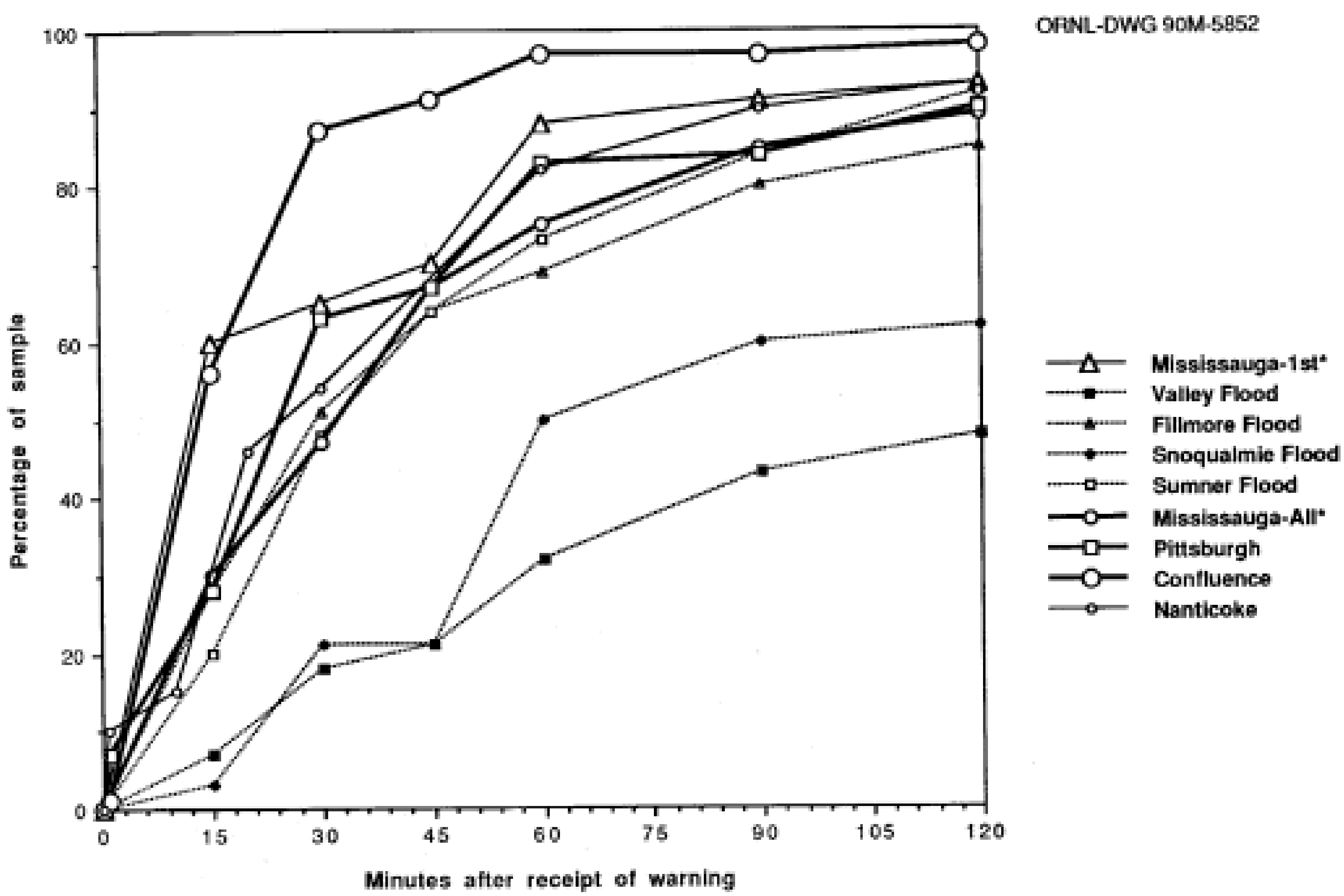


**Fig. 5.2. Mobilization time in selected events.** *First wave of evacuation for Mississauga accident designated (1st), all Mississauga evacuations designated (all).

extremely short lead times, the notion of early evacuation is somewhat irrelevant because the timing precludes prewarning departures.

### 5.1.3 Vehicle Use

Most planners estimate that to evacuate, each household will take an average of 1.3 to 1.5 vehicles (or about 2 to 2.5 people per vehicle). These estimates have been derived primarily from evacuation intent surveys. Very limited behavioral data exist to support this assumption. In the evacuation at Mississauga, Ontario, 97% of the families evacuated by automobile. The remaining 3% went by public transportation, taxi, or on foot. Of the 97% using autos, 79% took one car, 18% took two, and 3% took three (Burton et al. 1981), which resulted in an average of about 1.25 vehicles per family.

### 5.1.4 Destinations

Officials often are concerned about having enough public shelter space to house evacuees. In fact, few people go to official shelters following an evacuation (Fig. 5.3). In the events analyzed above, the number ranged between 6 and 30%. Several factors influence the use of shelters. Shelters will be used more heavily in nighttime evacuations than in those conducted during the day. Shelter use is higher for urban as opposed to rural evacuees. Shelter use is likely to be lower in areas characterized by strong social and family networks that provide temporary residences for evacuees. In some evacuations, shelter availability is more heavily publicized than in others, which may influence use levels. Finally, shelter use is likely to be higher in areas with a large number of tourists or transients.

## 5.2 SCREENING ANALYSIS

Four goal-oriented evacuation scenarios were evaluated for the 14 classes of accidents summarized in Tables 4.2 through 4.4 for three downwind distances (i.e., 3 km, 10 km, and 20 km) and three meteorological conditions (i.e., winds of 1, 3, and 6 m/s with stability class F, D, and C respectively), resulting in 504 release/response scenarios.

The response scenarios are considered goal oriented because they are consistent with the assumption that a state-of-the-art emergency response system is available and in use at each location. Hence, emergency response scenarios assume that (1) a decision to warn is made in 5 min, (2) a combination warning system is used that is composed of sirens for outdoor warning and a telephone ring-down system for indoor warning, and (3) the public responds 25% faster than they responded in the Confluence, Pennsylvania, train derailment.

Evacuation is summarized in terms of a time associated with clearing an area at risk to areas far enough away to be considered safe. One way to conceptualize this is in terms of the time it takes to arrive at a safe distance. This approach typically characterizes evacuation clearance times on the basis of evacuation time estimates (ETEs). ETEs are scheduled for the emergency preparedness program associated with the CSDP but have not yet been conducted. Hence, a range of clearance time assumptions can be used to

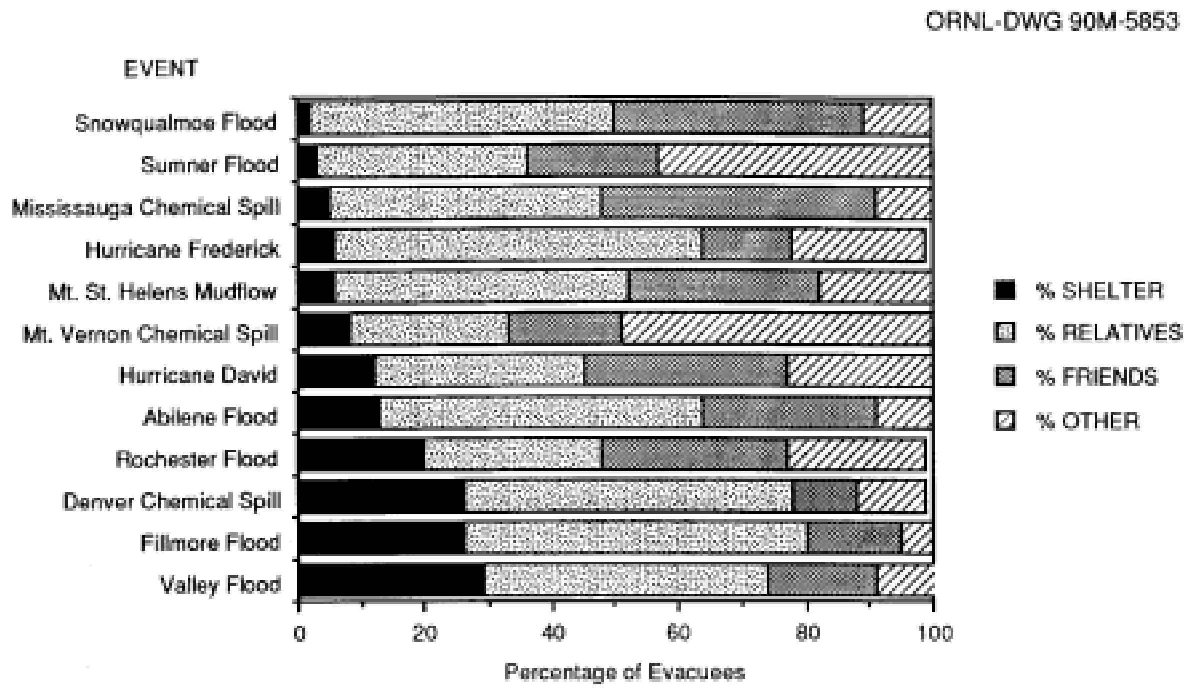


**Fig. 5.3. Destinations associated with selected evacuation events.** Data for graph from I. Burton et al., *The Mississauga Evacuation, Final Report*, Institute for Environmental Studies, University of Toronto, Toronto, 1981; R. Perry et al., *Evacuation Planning in Emergency Management*, Lexington Books, Lexington, Mass., 1981; R. Perry and M. Greene, *Citizen Response to Volcanic Eruptions: The Case of Mt. St. Helens*, Irvington Publishers, N.Y., 1983; R. Leik and J. Clark, *Community Response to Natural Hazard Warnings: Final Report*, University of Minnesota, Minneapolis, Minn., 1981; R. Perry and A. Mushkatel, *Disaster Management: Warning Response and Community Relocation*, Quorum Books, Westport, Conn., 1984; R. Perry and A. Mushkatel, *Minority Citizens in Disaster*, University of Georgia Press, Athens, Ga., 1986.

evaluate the effectiveness of protection achieved with evacuation. Hence, the evaluation of 5-, 10-, and 20-min clearance times represents the range of ETEs believed to be acceptable for various segments of the population. In addition, a 1-min clearance time is used to represent a nonconventional approach that is similar to being able to outrun the leading edge of the plume. All evacuation scenarios accumulate the concentrations present at the distance to be evacuated until an evacuation is complete and a safe distance is reached.

### 5.2.1 Nerve Agent GB Scenarios

A descriptive summary of the screening results for the GB evacuation scenarios is presented in Table 5.1. Of the 180 GB scenarios, less than 1 in 20 result in expected exposures that exceed the $LCt_{50}$ for either adult males or infants. The average expected exposures for evacuees are more than 20 times smaller than the expected exposures associated with staying in an unprotected environment. However, they are larger, on the average, than the $LCt_{50}$ for adult males in more than 5% of the scenarios. It follows, then, that evacuation reduces the exposure over the length of the plume by between 56 and 80% across exposure categories. No overall or relative exposure reductions are reported when no agent arrives at the designated downwind distance.

At both extremes, where the expected exposure exceeds the $LCt_{50}$ for adult males and when no exposure is expected at a given downwind distance in the first 3 h, the effectiveness of evacuation does not vary with the various clearance time response scenarios. In fact, even in the middle-level exposure categories, the variation is relatively small, with 1-min clearance times being only slightly more effective than 5- and 10-min clearances. The least effective evacuation time clears an area in 20 min.

Under the relatively slow onset associated with 1-m/s winds, 73.3% of the scenarios examined result in either no exposure or low exposure that are likely to escape observation. Another 20.0% are expected to result in exposures characterized by at least observable effects, and the remaining 6.7% of the scenarios examined are likely to result in exposures exceeding the $LCt_{50}$ for adult males. Both moderate onset (3-m/s winds) and rapid onset (6-m/s winds) result in no exposures associated with the vast majority of scenarios (85.0% and 93.3% respectively). Under 3-m/s winds, 8.3% of the scenarios examined result in observable effects, while 6.7% are expected to result in exposures of $LCt_{50}$ for adult males. Under 6-m/s winds, the remaining 6.7% of the scenarios analyzed result in exposures expected to be characterized by observable effects.

All scenarios examined at greater than 10 km and 20 km resulted in expected exposures below the no-observable-effects level. Hence, the screening analysis seems to indicate that evacuation can be effectively used for people greater than 10 km from the facilities. However, 13.3% of the scenarios examined 3-km downwind from the facilities resulted in expected exposures exceeding the $LCt_{50}$ for adult males, and another 35% resulted in expected exposures that would result in observable effects. Hence, just under half the scenarios examined at 3 km resulted in adverse impacts under a goal-oriented evacuation response for the GB accident scenarios examined.

**Table 5.1. Descriptive summary of results of goal-oriented screening analysis for scenarios involving GB and evacuation**

| | E(exposure) greater than $LCt_{50}$ for adult male[a] | E(exposure) greater than infant $LCt_{50}$[a] | E(exposure) greater than observed effects Ct[b] | E(exposure) less than observed effects Ct[b] | No exposure[c] |
|---|---|---|---|---|---|
| Scenarios | 8 | 0 | 21 | 131 | 20 |
| % of GB | 4.4 | 0.0 | 11.7 | 72.8 | 11.1 |
| | | **Average exposure** | | | |
| Unprotected, ($mg\text{-}min/m^3$) | 6,400 | NA | 310 | 70 | 0 |
| Evacuated, ($mg\text{-}min/m^3$) | 320 | NA | 9 | .2 | 0 |
| | | **Average exposure reduction** | | | |
| Overall, % | 56.0 | NA | 59.2 | 74.0 | 0.0 |
| Relative, % | 64.0 | NA | 63.9 | 79.7 | 0.0 |
| | | **Clearance time** | | | |
| 1-min[d], % | 4.4 | NA | 8.9 | 75.6 | 11.1 |
| 5-min[d], % | 4.4 | NA | 11.1 | 73.3 | 11.1 |
| 10-min[d], % | 4.4 | NA | 11.1 | 73.3 | 11.1 |
| 20-min[d], % | 4.4 | NA | 15.6 | 68.9 | 11.1 |
| | | **Meteorological conditions** | | | |
| WS 1 m/s, % | 6.7 | NA | 20.0 | 40.0 | 33.3 |
| WS 3 m/s, % | 6.7 | NA | 8.3 | 85.0 | 0.0 |
| WS 6 m/s, % | 0.0 | NA | 6.7 | 93.3 | 0.0 |
| | | **Downwind distance** | | | |
| 3 km, % | 13.3 | NA | 35.0 | 51.7 | 0.0 |
| 10 km, % | 0.0 | NA | 0.0 | 100.0 | 0.0 |
| 20 km, % | 0.0 | NA | 0.0 | 66.7 | 33.3 |

[a]Expected exposure exceeds $LCt_{50}$ for males and infants assuming light activity (see Tables 3.2 and 3.3).

[b]Expected exposure exceeds (greater than) or does not attain (less than) observed effects threshold for adults (see Tables 3.2 and 3.3).

[c]"No exposure" indicates that plume did not arrive in the first 3 h under the given condition.

[d]Implementation in terms of time to clear an area.

### 5.2.2 Nerve Agent VX Scenarios

A descriptive summary of the screening results for the VX evacuation scenarios is presented in Table 5.2. Of the 180 VX scenarios, about 10% result in expected exposures that exceed the $LCt_{50}$ for either adult males or infants. The average expected exposures when evacuated are much smaller than the expected exposures in the unprotected environment associated with staying. However, they are larger than the $LCt_{50}$ in 10.0% of the scenarios. Evacuation reduces the exposure over the length of the plume by between 44.6 and 84.1% across exposure categories. No overall or relative exposure reductions are reported when no agent arrives at the designated downwind distance.

When the expected exposure exceeds the $LCt_{50}$ for infants, and when no exposure is expected at a given downwind distance in the first 3 h, the effectiveness of evacuation does not vary with the various clearance time scenarios. Scenarios resulting in expected exposures greater than the $LCt_{50}$ range from 2.2% among the 1-min clearance time scenarios to 8.9% among the 20-min scenarios. In the observed effects exposure category, the variation is relatively small across scenarios, ranging from 22.2% to 26.7% as clearance time increases. Among those scenarios resulting in expected exposures of below-observed-effects levels, the variation is in the opposite direction, with 60.0% reaching this exposure category among 1-min scenarios and only 48.9% achieving this level among the 20-min scenarios.

Under the relatively slow onset associated with 1-m/s winds, 66.7% of the scenarios examined result in either no exposure or low exposures that are likely to escape observation. Another 13.3% are expected to result in exposures characterized by at least observable effects, and the remaining 20.0% of the scenarios examined are likely to result in exposures exceeding the $LCt_{50}$ for either infants (8.3%) or adult males (11.7%). Both moderate onset (3-m/s winds) and rapid onset (6-m/s winds) result in the majority of scenarios with no exposures (65.0% and 66.7% respectively). Under 3-m/s winds, 25.0% of the scenarios examined result in observable effects levels, while 10.0% result in exposures exceeding the $LCt_{50}$ for adult males or infants. At 6 m/s, the remaining 33.3% of the scenarios do not exceed the $LCt_{50}$ for either infants or adult males.

All scenarios examined at 20 km resulted in expected exposures below the observable effects level, and only 4.8% resulted in observable effects levels at 10 km. Hence, the screening analysis seems to indicate that evacuation can be effectively used for people greater than 10 km from the facilities with state-of-the-art emergency planning systems at those distances. However, 30.0% of the scenarios examined 3-km downwind from the facilities resulted in expected exposures exceeding the $LCt_{50}$ for either infants or adult males, and another 60% resulted in expected exposures that would result in observable effects. Hence, about 90% of the scenarios examined at 3 km resulted in adverse impacts under a goal-oriented evacuation response for the VX accident scenarios examined. This clearly indicates an unacceptable failure rate.

### 5.2.3 Blister Agent Mustard (H/HD) Scenarios

A descriptive summary of the screening results for the mustard evacuation scenarios is presented in Table 5.3. Of the 144 scenarios, 10% result in expected exposures that

**Table 5.2. Descriptive summary of results of goal-oriented screening analysis for scenarios involving VX and evacuation**

| | E(exposure) greater than $LCt_{50}$ for adult male[a] | E(exposure) greater than infant $LCt_{50}$[a] | E(exposure) greater than observed effects Ct[b] | E(exposure) less than observed effects Ct[b] | No exposure[c] |
|---|---|---|---|---|---|
| Scenarios | 10 | 8 | 43 | 99 | 20 |
| % of X | 5.6 | 4.4 | 23.9 | 55.0 | 11.1 |
| | | | **Average exposure** | | |
| Unprotected, ($mg\text{-}min/m^3$) | 15,000 | 750 | 40 | 270 | 0 |
| Evacuated, ($mg\text{-}min/m^3$) | 150 | 20 | 2 | .01 | 0 |
| | | | **Average exposure reduction** | | |
| Overall, % | 84.1 | 71.4 | 44.6 | 83.3 | 0.0 |
| Relative, % | 86.1 | 77.2 | 52.7 | 88.3 | 0.0 |
| | | | **Clearance time** | | |
| 1-min[d], % | 2.2 | 4.4 | 22.2 | 60.0 | 11.1 |
| 5-min[d], % | 4.4 | 4.4 | 22.2 | 57.8 | 11.1 |
| 10-min[d], % | 6.7 | 4.4 | 24.4 | 53.3 | 11.1 |
| 20-min[d], % | 8.9 | 4.4 | 26.7 | 48.9 | 11.1 |
| | | | **Meteorological conditions** | | |
| WS 1 m/s, % | 11.7 | 8.3 | 13.3 | 33.3 | 33.3 |
| WS 3 m/s, % | 5.0 | 5.0 | 25.0 | 65.0 | 0.0 |
| WS 6 m/s, % | 0.0 | 0.0 | 33.3 | 66.7 | 0.0 |
| | | | **Downwind distance** | | |
| 3 km, % | 16.7 | 13.3 | 60.0 | 10.0 | 0.0 |
| 10 km, % | 0.0 | 0.0 | 4.8 | 93.2 | 0.0 |
| 20 km, % | 0.0 | 0.0 | 0.0 | 66.7 | 33.3 |

[a]Expected exposure exceeds $LCt_{50}$ for males and infants assuming light activity (see Tables 3.2 and 3.3).

[b]Expected exposure exceeds (greater than) or does not attain (less than) observed effects threshold for adults (see Tables 3.2 and 3.3).

[c]"No exposure" indicates that plume did not arrive in the first 3 h under the given condition.

[d]Implementation in terms of time to clear an area.

Table 5.3. Descriptive summary of results of goal-oriented screening analysis for scenarios involving H/HD and evacuation

| | E(exposure) greater than $LCt_{50}$ for adult male[a] | E(exposure) greater than infant $LCt_{50}$[a] | E(exposure) greater than observed effects Ct[b] | E(exposure) less than observed effects Ct[b] | No exposure[c] |
|---|---|---|---|---|---|
| Scenarios | 11 | 3 | 114 | NA | 16 |
| % of H/HD | 7.6 | 2.1 | 79.2 | NA | 11.1 |
| | | **Average exposure** | | | |
| Unprotected, (mg-min/m$^3$) | 550,000 | 8,500 | 6,700 | NA | 10 |
| Evacuated, (mg-min/m$^3$) | 6,350 | 1,050 | 30 | NA | 0 |
| | | **Average exposure reduction** | | | |
| Overall, % | 87.0 | 46.9 | 78.1 | NA | 0.0 |
| Relative, % | 88.2 | 60.9 | 81.9 | NA | 0.0 |
| | | **Clearance time** | | | |
| 1-min[d], % | 5.6 | 2.8 | 80.6 | NA | 11.1 |
| 5-min[d], % | 8.3 | NA | 80.6 | NA | 11.1 |
| 10-min[d], % | 8.3 | 2.8 | 77.8 | NA | 11.1 |
| 20-min[d], % | 8.3 | 2.8 | 77.8 | NA | 11.1 |
| | | **Meteorological conditions** | | | |
| WS 1 m/s, % | 16.7 | 0.0 | 50.0 | NA | 33.3 |
| WS 3 m/s, % | 6.3 | 6.3 | 87.5 | NA | 0.0 |
| WS 6 m/s, % | 0.0 | 0.0 | 100.0 | NA | 0.0 |
| | | **Downwind distance** | | | |
| 3 km, % | 22.9 | 6.3 | 70.8 | NA | 0.0 |
| 10 km, % | 0.0 | 0.0 | 100.0 | NA | 0.0 |
| 20 km, % | 0.0 | 0.0 | 66.7 | NA | 33.3 |

[a]Expected exposure exceeds $LCt_{50}$ for males and infants assuming light activity (see Tables 3.2 and 3.3).

[b]Expected exposure exceeds (greater than) or does not attain (less than) observed effects threshold for adults (see Tables 3.2 and 3.3).

[c]"No exposure" indicates that plume did not arrive in the first 3 h under the given condition.

[d]Implementation in terms of time to clear an area.

exceed the $LCt_{50}$ for either adult males or infants. The average expected exposures for evacuees are much smaller than the expected exposures in the unprotected environment associated with staying; however, the exposures are larger than the $LCt_{50}$ in 9.7% of the H/HD scenarios. Evacuation reduces the exposure over the length of the plume by between 46.9 and 87.0% across exposure categories. Overall or relative exposure reductions are zero when no agent arrives at the designated downwind distance.

When the expected exposure exceeds the $LCt_{50}$ for infants and when no exposure is expected at a given downwind distance in the first 3 h, the effectiveness of evacuation does not vary with the various clearance time scenarios. For scenarios resulting in expected exposures greater than the $LCt_{50}$, the effectiveness varies from 5.6% among the 1-min clearance time scenarios to 8.3% for 5-, 10-, and 20-min scenarios. There is no variation among the scenarios in the exposure category when the exposure exceeds the $LCt_{50}$ for infants. In the observed effects exposure category, the variation is relatively small across scenarios, being 80.6% for the shortest two clearance times and 77.8% for the longer clearance time scenarios. Because of the delayed effects of mustard as a carcinogen, no level can be established for observable effects.

Under the relatively slow onset associated with 1-m/s winds, 33.3% of the scenarios examined result in either no exposures in the first 3 h or exposures that are likely to escape observation. Another 50.0% are expected to result in exposures resulting in at least observable effects, and the remaining 16.7% of the scenarios examined are likely to result in exposures exceeding the $LCt_{50}$ for adult males. Both moderate onset (3-m/s winds) and rapid onset (6-m/s winds) scenarios result in the majority ending with no exposures, (87.5% and 100% respectively). Under 3-m/s winds 12.6% of the scenarios examined result in exposures exceeding the $LCt_{50}$ for adult males or infants.

All scenarios examined at 10 km and 20 km resulted in expected exposures below the $LCt_{50}$ for either infants or adult males. Most of these scenarios involving distances of 10 and 20 km result in observable effects below the $LCt_{50}$ for infants. Once again, the screening analysis seems to confirm that evacuation can be effectively used for people located greater than 10 km from the potential source point with these goal-oriented emergency planning systems at those distances. However, about 30.0% of the scenarios examined at 3 km downwind resulted in expected dosages exceeding the $LCt_{50}$ for either infants or adult males. Moreover, all of the scenarios for 3 km and 10 km have expected exposures that likely would result in observable effects and thereby would result in adverse impacts under a goal-oriented evacuation response for the mustard accident scenarios examined.

## 5.3 ANALYSIS OF SELECTED SCENARIOS

Using the scenarios and analyses discussed in Sect. 5.2, a preliminary analysis of the effectiveness of evacuation under different conditions can be made. The analysis is based on the implementation of an indoor-outdoor warning system, a decision-support system with rapid response time, and public education.

Evacuation appears to have a mixed effectiveness at a distance of 3 km. It is most effective under the following conditions, windspeeds are 1 m/s or less, and people are able to travel far enough in 10 min to avoid the plume. Figure 5.4 presents the probability of

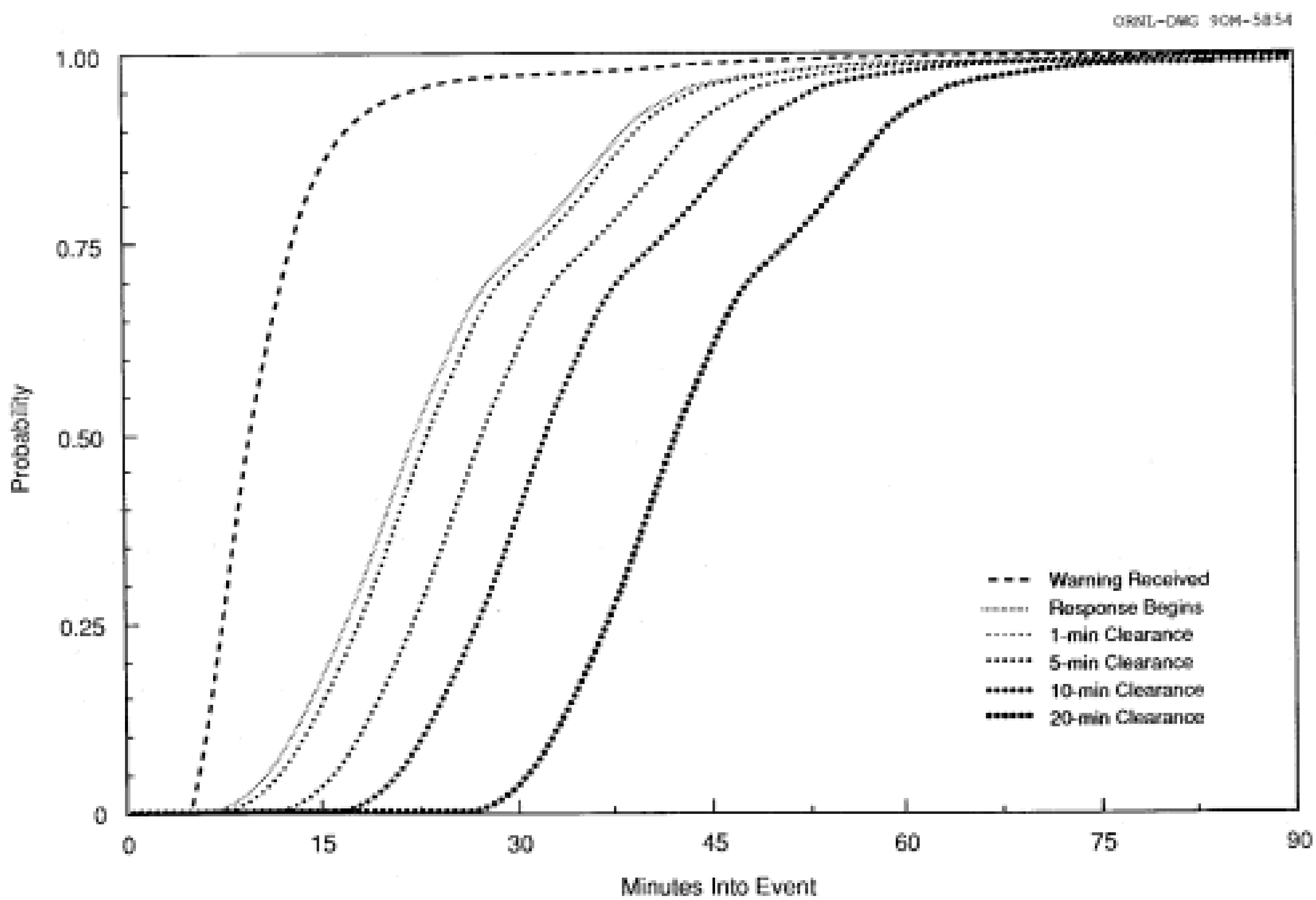


**Fig. 5.4. Probability of completing evacuation activities by time into the event.**

completing evacuations with 1-, 5-, 10-, and 20-min clearance times given a goal-oriented emergency response system. In such cases, 70 to 100% of the population will avoid exposure under 1-m/s winds. Those not avoiding exposure potentially will be exposed to concentrations above the $LCt_{50}$ for large accident scenarios and at levels above no effects for the smaller releases. The exposures for those exposed will vary according to the length of time in the plume. For those in the plume for the entire exposure time, the exposure will equal the unprotected exposure; for others, the exposure will range between some minimal amount and the unprotected exposure. Fatalities will range between 1 and 10% depending on the circumstances.

Considering a Class III release of GB under stable wind conditions (1 m/s), evacuation is a viable response for people located 3 km downwind (Fig. 5.5). Of course, the more quickly people evacuate the area, the better the protection. Completing the evacuation of the area in about 10 min means that by the time the plume arrives (about 50 min after the release), 90 to 100% of the population is likely to have traversed beyond the leading edge of the plume. By the time the plume passes over the people who have not evacuated, they will be exposed to a potential exposure of up to 300 mg-min/$m^3$, or well above the $LCt_{50}$ for adult males. If it takes 20 min to clear the area, the portion avoiding exposure drops to between 70 and 80%, with corresponding increases in the portion exposed. The resulting expected exposure nearly reaches the $LCt_{50}$ for newborn infants, while 10-min clearance results in an expected exposure that is less than half that of the longer 20-min clearance evacuation scenario.

The ability to evacuate people is reduced when the arrival time is faster due to increased windspeeds. Under 3-m/s winds, it is anticipated that only about 10% of the population will have evacuated before the plume arrives (in about 12-min). This leaves approximately 90% of the population at this distance receiving the exposures associated with the unprotected environment. However, because of the increased dispersion associated with faster windspeeds, the unprotected exposure also is reduced (Fig. 4.1). Hence, evacuation under these conditions is implemented to help reduce impacts that are likely to be nonlethal for most people. Figure 5.6 presents the evacuation scenarios for the VX Class III event discussed above for 3-m/s winds. These results indicate that even though the onset is more rapid and allows less time to evacuate, the expected exposure is not as high as the expected exposure received under the slower onset. The unprotected exposure is unlikely to accumulate to the $LCt_{50}$ level for newborn infants. Exposure reductions associated with evacuation will vary with clearance time. If people can clear the plume rapidly, expected exposure is substantially reduced. The longer it takes to clear the plume, the more similar the expected exposure is to those people without protection.

The results are quite similar for a VX Class III accident under 3 m/s winds for people 3 km downwind (Fig. 5.6). As in the GB scenarios, when the plume arrives, most people (90 to 100%) are unlikely to have evacuated or cleared the plume area. Many people are likely to receive the unprotected exposure that nearly attains the $LCt_{50}$ for newborn infants. In larger-release scenarios, evacuation will be of limited effectiveness due to potentially large unprotected exposures. For example, even the very best evacuation systems cannot adequately avoid the lethal exposures associated with a catastrophic release of GB (Fig. 5.7). Under these conditions, the expected exposures associated with 5- and 10-min evacuations of people 3 km downwind would exceed the

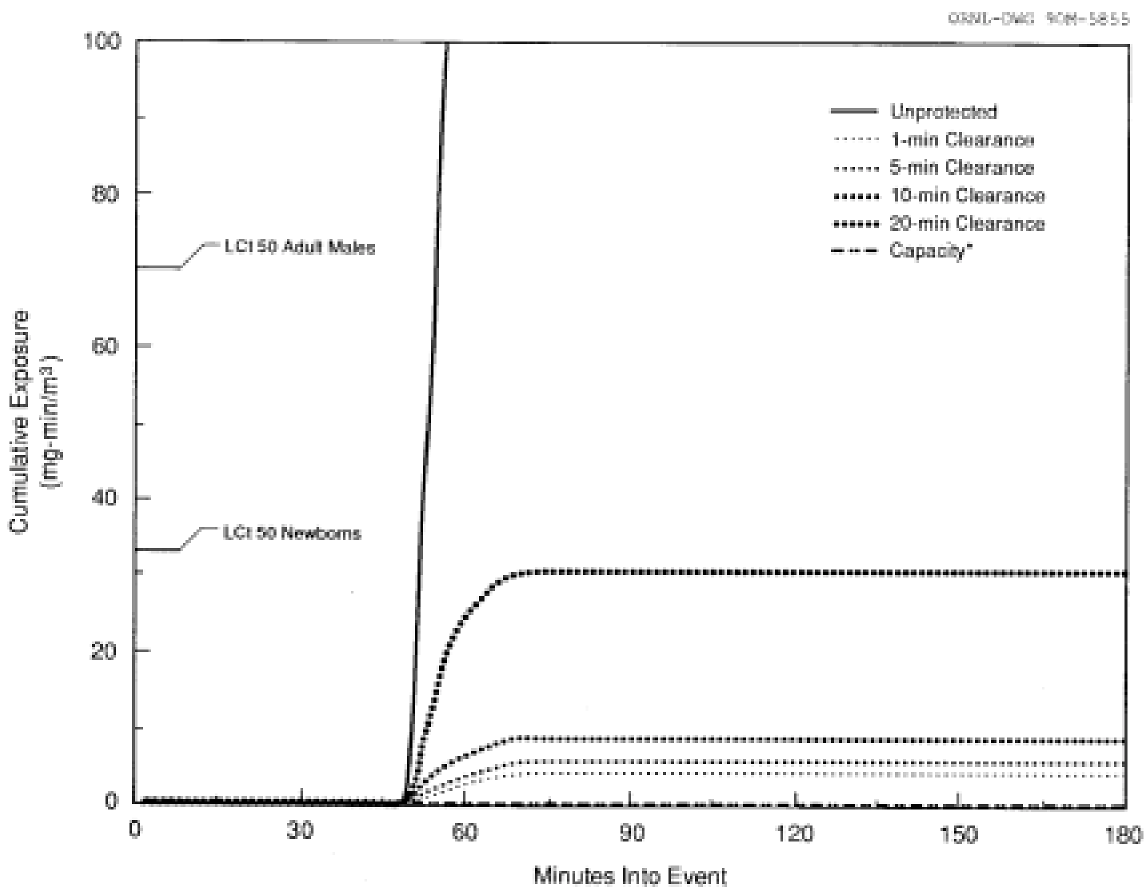


Fig. 5.5. Evacuation scenarios at 3-km distance for GB class III events when 1-m/s winds prevail. Note that $LCt_{50}$ equals concentration–time integral, lethal for 50% of reference population. *All evacuation clearance time is capable of complete protection in this scenario.

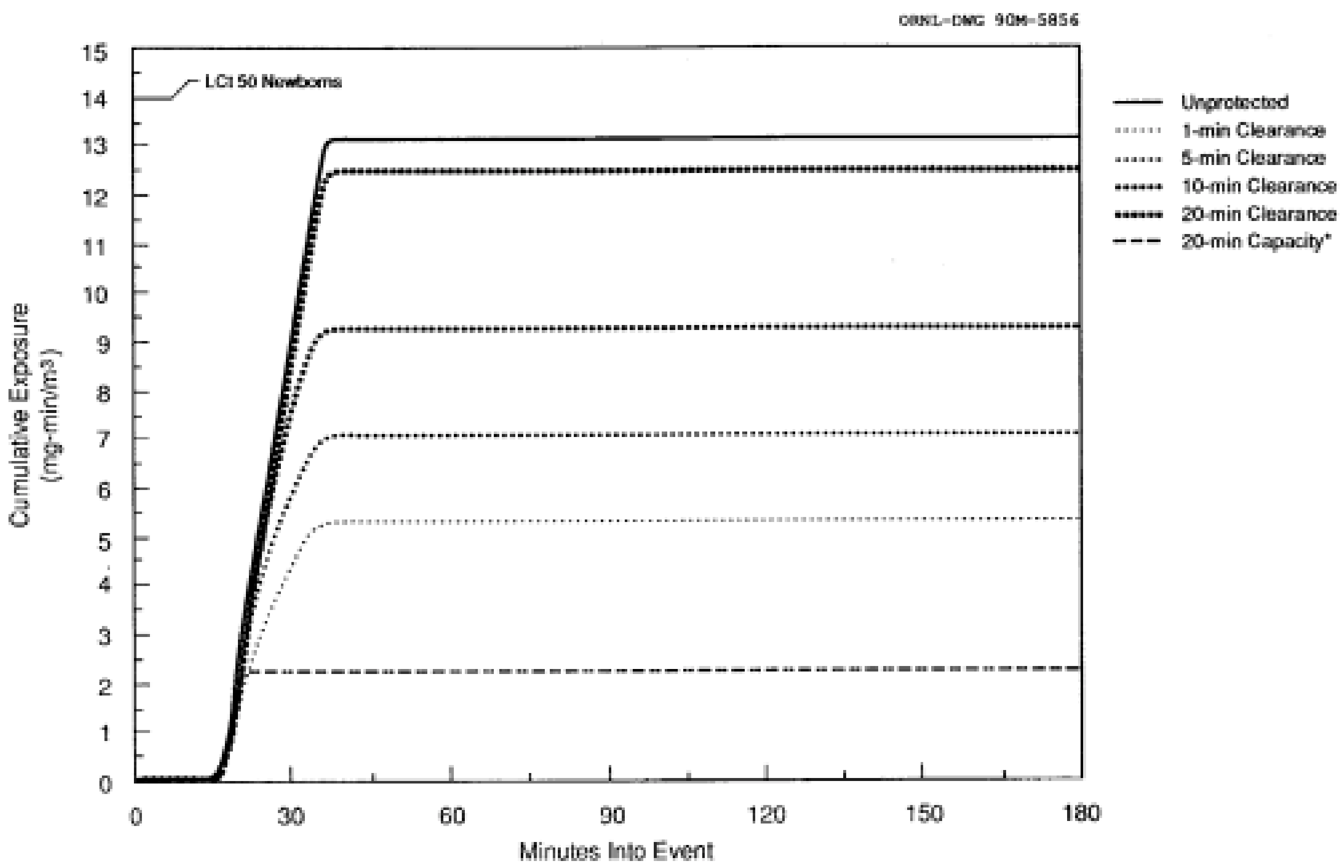


**Fig. 5.6. Evacuation scenarios at 3-km distance for VX class III events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration–time integral, lethal for 50% of reference population. *All evacuation clearance times < 12 minutes have the potential to completely avoid exposure.

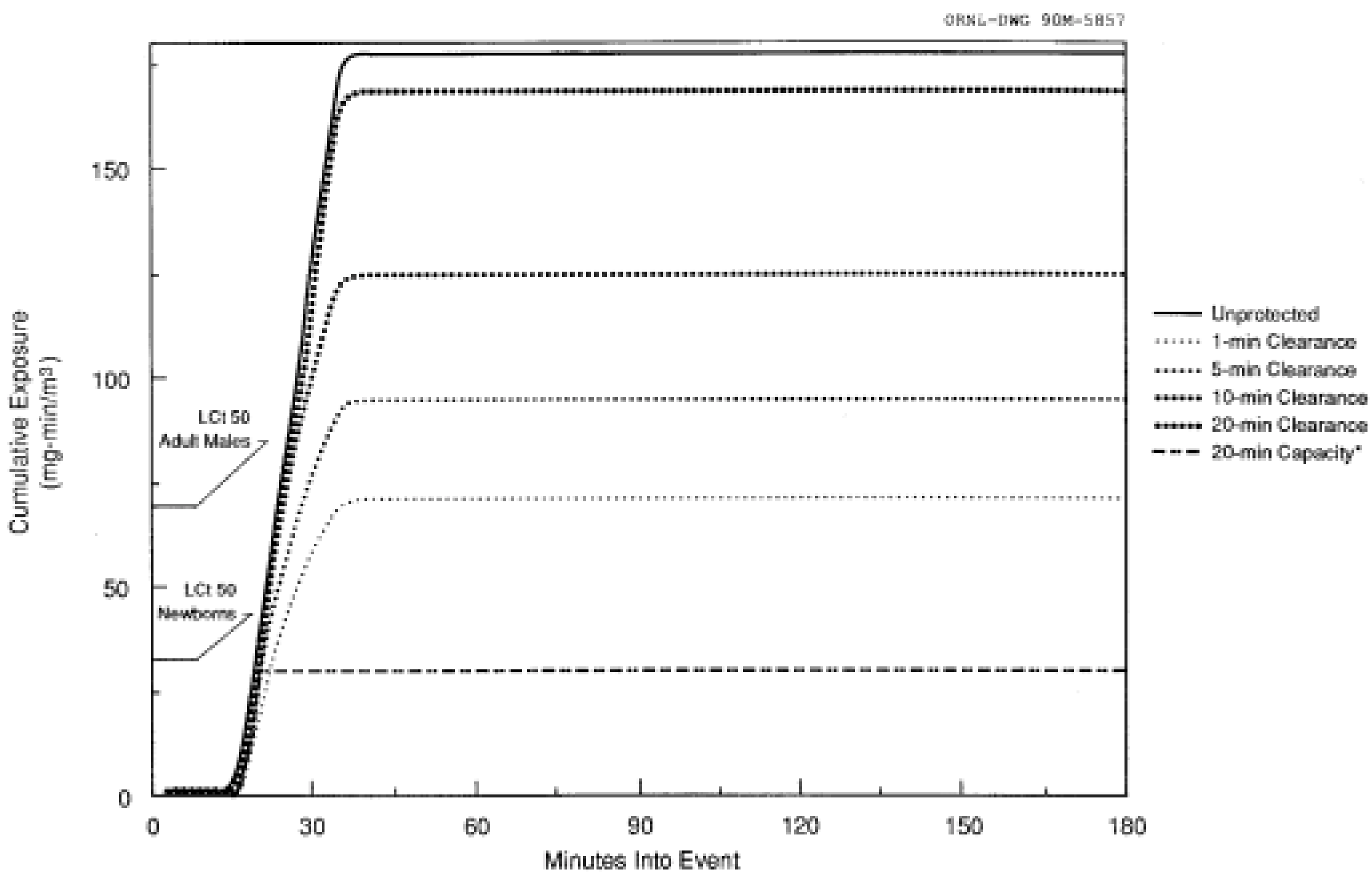


**Fig. 5.7. Evacuation scenarios at 3-km distance for GB class V events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration–time integral, lethal for 50% of reference population. *All evacuation clearance times < 12 minutes have the potential to completely avoid exposure.

$LCt_{50}$ for adult males, while 1-min clearance of the plume area would attain exposures approximately equal to the $LCt_{50}$ for adult males. Moreover, even assuming that everyone could be evacuated within 20-min of the time of the accident, expected exposures are just below the $LCt_{50}$ for newborn infants. Fatalities are likely in this scenario.

At 10 km, evacuation appears to be an effective strategy. When the windspeed is 1 m/s, the conditions where the agent is most likely to traverse 10 km, there is sufficient time (i.e., more than 2.5 h) to evacuate people before the plume arrives. Under only the largest accidents will significant amounts of agent reach 10 km with faster windspeeds. If windspeeds are 3 m/s, an estimated 90 to 100% of the people will have evacuated by the time the plume reaches 10 km. In only the largest release scenarios will the remaining population be exposed to agent at levels between the no effects and $LCt_{50}$ levels.

When the windspeed increases to 6 m/s, only 1 to 20% are likely to have evacuated before the plume's arrival at 10 km. However, even in the largest accidents, exposures at the resulting levels are unlikely to result in observable effects.

## 5.4 CONCLUSIONS ON EVACUATION

Evacuation is a viable option at distances over 10 km, and fatalities are unlikely under any scenario. In catastrophic accidents, given windspeeds of 3 m/s or greater, evacuation is unlikely to be effective at 3-km distances. In other situations, a comparison of evacuation with other actions seems warranted before a protective action recommendation is made for populations within 10 km. At distances under 10 km, evacuation is most appropriate under stable weather conditions with low winds speeds. However, because fatalities are still likely to occur, a comparison of protective actions seems to be warranted for any scenario.

# 6. IN-PLACE PROTECTION FOR CHEMICAL AGENT EMERGENCIES

This section describes the analysis of in-place shelters as a protective measure that reduce exposure. This section first considers the concept of in-place sheltering in terms of constraints associated with its use, which completes the model development; the section continues with the preliminary analysis in terms of a screening analysis and then a closer examination of selected scenarios. The section ends with some preliminary conclusions concerning the use of in-place shelters to reduce exposure in chemical agent emergencies.

This section examines the amount of protection afforded by shelters characterized by various exchange rates and relates this protection to the emergency response activities required to achieve the rates during the emergency. Three basic alternatives are examined: pressurized, enhanced, and expedient shelters. Pressurized shelters may be characterized as a special case where there is no exchange of air from the unprotected to the protected environment. Enhanced shelters are weatherized structures in which the exchange of air between interior and exterior environments is reduced. Because enhanced structures are weatherized in advance of the accidental release of chemicals, they can be assumed to have low exchange rates and to require only that doors and windows be closed to achieve the desired level of protection. Expedient shelters can achieve further reductions in air exchange but require more time to implement procedures to achieve the maximum protection (see Appendices F and G).

## 6.1 IN-PLACE SHELTERING CONCEPTS

In-place protection involves the reduction of air exchange between the exterior toxic environment and the interior sheltered environment. The degree to which the flow of potentially contaminated air flows into the shelter can be used to generally characterize the type of in-place protection.

Extensive research of energy conservation has shown that air exchange in most U.S. dwellings is distributed from fairly leaky units at about 1.5 air changes per hour (ACH) to the more tightly sealed units at 0.5 ACH (EPRI 1983; Bonneville Power Administration 1983; and National Research Council 1981 as summarized in Mueller Associates, Inc. 1985 and Kolb and Baylon 1989). These rates have been shown to be related to wind speed (Grimsrud, et al. 1984; Strandon and Bertiris 1980), orientation to the wind (Mattingly and Peters 1977), structural characteristics (EPRI 1988a; Reinhold and Sonderegger 1983; Sherman et al. 1984; Lawrence Berkeley Laboratory 1984; Sandia National Laboratories and AnaChem, Inc. 1981), and temperature difference between the indoor and outdoor environments (Lawrence Berkeley Laboratory 1984; Stranden and Berteig 1980; Grimsrud, et al. 1982 and 1984). These air exchange rates have become important in recent years because of concerns over indoor pollution (Hawthorne et al. 1983; Diamond and Grimsrud 1983; EPRI 1988b and 1985; Gammage and Kaye 1985; and Walkinshaw 1986), with more tightly sealed units being of greater concern than less tightly sealed dwelling units.

### 6.1.1 Structural Constraints

The protection provided by in-place shelters depends on (1) the "leakiness" or infiltration rate of the structure (expressed as air changes / hour), (2) the timing of the implementation, and (3) the physiological response among human populations. The physiological response is sensitive to both the peak concentration (mg/m$^3$) and the accumulated exposure (mg-min/m$^3$). When the physiological effects associated with typical exposures are rapidly reversible, exposures may be thought of as dominated by peak concentration. Such chemical as hydrogen chloride, hydrogen sulfide, chlorine and ammonia have toxicities that are more sensitive to peak concentrations. When physiological effects are dominated by peak exposures to chemicals, concern focuses on high concentration over fairly short durations. But when physiological response is dominated by accumulated concentration, even fairly low exposures can accumulate, if the exposure continues over a long duration, and result in severe physiological consequences. Chemicals characterized by irreversible or very slowly reversible effects, include the chemical warfare agents examined herein (e.g., tabun, sarin, mustard, and soman), and organo-metallic vapors (e.g., tetro ethyl lead). Hence, depending on the character of the chemical to be protected from, the amount of protection provided by in-place shelters is dominated by the reduction of peak concentration, or accumulated exposure, or both.

For any concentration of chemical(s) in an unprotected environment, the concentration inside an in-place shelter is a function of the concentration in the shelter at the previous time period plus the amount entering the shelter minus the amount leaving the shelter. Simply put, the concentration inside an in-place shelter may be expressed as a mass balance where accumulation is equal to input minus output. The result is that contaminants infiltrate into the reduced infiltration shelter proportional to the difference between the concentration outside and inside; and then contaminants exfiltrate from the shelter as a decay function that is asymptotic to the x-axis. Recall the King who gave away half his wealth with each passing year, but died before his money was gone. Mass balance has a similar implication for reduced infiltration shelters; it takes longer for contaminated air to exfiltrate after the plume has passed than it did for contaminated air to infiltrate as the plume arrived.

For contaminants, such as chemical agents, that are characterized by human health consequences that are associated with cumulative exposure over time, the implication is that reduced infiltration shelters must be vacated or ventilated once the plume has passed to achieve protection. Simply put, people in reduced infiltration shelters that are not vacated enter into a trade off between being exposed to large amounts of agent for relative short durations, or being exposed to relatively small amounts of agent for relatively long durations. Appendix I examines the implementation of in-pace shelters logically to derive the key implications for the use of reduced infiltration in-place shelters.

For human health effects associated predominantly with cumulative exposures, the important implications of in-place shelters in response to chemical hazards stem from the findings of Birenvige (1983) and Chester (1988). Specifically that the cumulative exposure, Ct, within a leaky (ACH > 0) structure is exactly the same as Ct outside that structure, over long durations, and when the structure is not ventilated or vacated after the plume has passed. Because cumulative exposures in the protected and unprotected

environments are equal, with longer durations exactly compensating for the reduced (minute by minute) concentrations, reduced infiltration shelters:

- only provide protection if ventilated after plume passes, and
- are ineffective for long duration plumes, or continuous releases.

The implications for an emergency response system are understood more fully by examining the relationship between the timing of implementation and exposure. Exposure may be increased in a reduced infiltration shelter, if they are not

- fully implemented when the plume arrives, or
- ventilated as the plume passes.

The maximum exposures are generally attained when the sheltering process is completed just as the plume passes.

Conversely rapid implementation can achieve exposure reduction only if the sheltered environment is vacated or ventilated after the plume passes. Given that a reduced infiltration shelter environment is vacated or ventilated after the plume passes, the more quickly it can be implemented the better the chances of reducing exposure. Protection is maximized if implementation is completed prior to the plumes's arrival and vacated immediately upon its passage.

Generally, the greater the infiltration rate associated with a reduced infiltration shelter, the less protection. This occurs because,

- the concentrations in the protected environment reach higher levels, and
- ventilation must be more precisely timed to avoid exposure.

Finally, to the extent that shelters are sealed (ACH = 0) during the onset of a plume, they can seal agent concentrations in the sheltered environment with the occupants and thereby increase exposure. Fortunately, pressurized shelters usually operate on an exfiltration principle that creates a pressure from the inside by maintaining a flow of fresh (non-contaminated) air into the shelter. This exfiltration flow would exhaust any concentrations of agent in the sheltered environment at a rate equal to the exfiltration rate.

### 6.1.2 Current Use

Relatively little is known about current practices regarding the use of in-place shelter to protect people from exposure to potential chemical hazards. This section briefly summarizes the critical findings from a preliminary investigation of eight case studies where in-place protection measures were used in recent chemical emergencies. These cases are discussed in greater detail in Appendix E.

In the eight chemical emergencies where in-place shelters where used to protect the public, it was not always clear who made the decision to recommend in-place protection; however, in most cases it seemed to be at the discretion of the incident commander or

the equivalent operational person at the scene. In one instance, the mayor was at the scene, which implies an involvement in the decision. One interesting factor that surfaced in these case studies is that, in some states, the local officials have the authority to recommend that in-place protection measures be used but only the governor has the authority to order an evacuation. In-place measures were used in conjunction with evacuation of at least some people in the area in almost every case studied. Generally, in-place protective measures were recommended for areas further away from the source of hazard where chemical concentrations would be expected to be lower than evacuated areas.

Emergency personnel considered several factors to be important in determining the potential effectiveness of in-place protection measures; however, no consistent criteria were used to make these recommendations. Factors that usually were taken into account include weather conditions, population density, time of day, and uncertainty about the chemicals involved and/or the accumulating concentrations in public areas. Although weather conditions usually were mentioned as a contributing factor, in some instances gusty winds and widely dissipating plumes lead to the in-place recommendation; in others instances, a vapor cloud hovering near the ground seemed to foster in-place decisions. Population density was mentioned as a contributing factor in several instances, but it was not clear at what point density is important, or for that matter whether high-population density or low-population density leads to decisions for use of in-place shelters. Normally, time of day was mentioned as an important factor in the decision to recommend in-place shelter. It usually was mentioned as a way of indicating that people were already indoors. It was often mentioned together with temperature, apparently to indicate that people already had their windows closed. In almost every case, the in-place protection advisory was affected by the amount of uncertainty involved in the emergency; emergency officials seemed to indicate that until they could determine that an evacuation was warranted, in-place protection was advisable. Factors not mentioned as important in the in-place sheltering decision include the extent to which the hazard was sensitive to peak concentration or cumulative exposure sensitive, the ability of homes in the particular area to reduce exposure via reduced infiltration (e.g., the leakiness of buildings in the area), or the extent to which chemicals may be trapped in the building providing protection at the time of the recommendation.

While most of the in-place protection advisories mentioned staying inside, closing doors and windows and turning off ventilation systems, none mentioned any proactive measures such as putting damp towel under doors, taping large cracks, or covering exterior fans or vents. Most also mentioned staying tuned to radio or television as a way of monitoring the situation. Emergency personnel have a proclivity to evacuate whenever possible. Emergency personnel seem to be saying, "If it's bad enough to undertake the more active in-place measures, then we should probably evacuate those areas."

From these limited data, recommendations for in-place protection in the event of a chemical accident employ a passive response more often than a proactive response to the emergency events. Five qualitative findings seem to support this conclusion. First, emergency personnel frequently indicated that they selected in-place protection because the situation simply was not serious enough to warrant more active responses. Second, in most cases in-place protection was used in the outermost areas of the hazard zone.

Third, emergency personnel voiced concern that they were uncertain regarding whether they could evacuate people already indoors without exposing them. Fourth, emergency personnel indicated, in most cases, that time of day and outdoor temperature were important factors in their decision to use in-place shelter, the implication being that people already would have been indoors with the doors and windows closed. Finally, most decisions about in-place protection also were based on a high degree of uncertainty concerning the nature of the threat and its seriousness.

## 6.2 SCREENING ANALYSIS

Three goal-oriented in-place shelter emergency response scenarios were evaluated for the 14 release scenarios summarized in Table 4.2 for three downwind distances (i.e., 3 km, 10 km, and 20 km) and three meteorological conditions (i.e., winds of 1, 3, and 6 m/s with stability class F, D, and C respectively), resulting in 378 release/response scenarios.

The response scenarios are considered goal oriented because they make assumptions consistent with a state-of-the-art emergency response system. Hence, emergency response scenarios assume that (1) a decision to warn is made in 5 min, (2) a combination warning system using sirens for outdoor warning and a telephone ring-down system for indoor warning, and (3) the public responds 25% faster than they responded in the Confluence, Pennsylvania, train derailment.

In-place protection is summarized in terms of three basic cases involving infiltration rates of 0, 0.2 and 0.5 ACH. Normal sheltering in leaky dwelling units (1.5 ACH) was not considered in this analysis because (1) it is inconsistent with the goal-oriented approach being taken here and (2) the only cases where normal sheltering will be effective, enhanced shelters will also be effective. Hence, normal sheltering can be examined further in those instances where enhanced shelters are effective to determine the impact of such a planning decision. Because pressurized and enhanced shelters involve only the closing of doors and windows, when ACH is set to 0 or 0.5, implementation involves only closing doors and windows. Passive implementation of these alternatives initiates the probability of having completed the implementation by the probability of being indoors at the time of the accident. Implementing expedient measures, such as taping and sealing a room within a dwelling, takes slightly longer (see Fig. 3.7). Moreover, no passive augmentation is possible because the expedient activities require direct participation by the people to be protected.

### 6.2.1 Nerve Agent GB Scenarios

Table 6.1 presents a descriptive summary of the results of the screening analysis for accident scenarios involving GB. Of the 135 goal-oriented emergency response scenarios examined involving GB, the expected exposures associated with less than 10% would exceed the $LCt_{50}$ for any population segment, and only 6.7% exceeded the $LCt_{50}$ for adult males under light activity. The average expected exposures in the protected environment are less than half the expected exposures in the unprotected environment; they are less than a quarter of the exposures received in the unprotected environment if

Table 6.1. Descriptive summary of results of goal-oriented screening analysis for scenarios involving GB and in-place shelter

| | E(exposure) greater than $LCt_{50}$ for adult male[a] | E (exposure) greater than $LCt_{50}$ infant[a] | E(exposure) greater than observed effects Ct[b] | E(exposure) less than observed effects Ct[b] | No exposure[c] |
|---|---|---|---|---|---|
| Scenarios | 9 | 2 | 19 | 90 | 15 |
| % of GB | 6.7 | 1.5 | 14.1 | 66.7 | 11.1 |
| | | **Average exposure** | | | |
| Unprotected, (mg-min/$m^3$) | 4,900 | 240 | 150 | 25 | 0 |
| In Shelter, (mg-min/$m^3$) | 1,800 | 100 | 30 | 0.5 | 0 |
| Vacated, (mg-min/$m^3$) | 520 | 60 | 10 | 0.2 | 0 |
| | | **Average exposure reduction** | | | |
| Overall, % | 74.0 | 59.0 | 63.5 | 71.1 | 0.0 |
| Relative, % | 82.1 | 70.9 | 70.5 | 79.2 | 0.0 |
| | | **Response scenario** | | | |
| ACH = 0[d], % | 2.2 | 2.2 | 8.9 | 75.6 | 11.1 |
| ACH = 0.2[d], % | 8.9 | 2.2 | 15.6 | 62.2 | 11.1 |
| ACH = 0.5[d], % | 8.9 | 0.0 | 17.8 | 62.2 | 11.1 |
| | | **Meteorological conditions** | | | |
| WS 1 m/s, % | 15.6 | 2.2 | 24.4 | 24.4 | 33.3 |
| WS 3 m/s, % | 4.4 | 2.2 | 11.1 | 82.2 | 0.0 |
| WS 6 m/s, % | 0.0 | 0.0 | 6.7 | 93.3 | 0.0 |
| | | **Downwind distance** | | | |
| 3 km, % | 15.5 | 4.4 | 35.5 | 33.3 | 0.0 |
| 10 km, % | 4.4 | 0.0 | 6.7 | 66.7 | 0.0 |
| 20 km, % | 0.0 | 0.0 | 0.0 | 66.7 | 33.3 |

[a]Expected exposure exceeds $LCt_{50}$ for males and infants assuming light activity (see Tables 3.2 and 3.3).

[b]Expected exposure exceeds (greater than) or does not attain (less than) observed effects threshold for adults (see Tables 3.2 and 3.3).

[c]"No exposure" indicates that plume did not arrive in the first 3 h under the given condition.

[d]In-place shelters are characterized in terms of the air change rate (ACH), with 0 being pressurized shelters, 0.2 representing expedient shelters, and 0.5 representing enhanced shelters.

the shelter can be vacated immediately upon the passage of the plume; however, on average the exposures are five to seven times greater than the $LCt_{50}$ for adult males for resting and light activity respectively. It follows then that these in-place shelters, with exchange rates of 0, 0.2 and 0.5 ACH, reduce the exposure over the length of the plume by almost three-fourths but are likely to fail to prevent deaths in about 10% of the accident scenarios examined.

Most of the accidental releases of agent GB and the associated emergency response scenarios involving in-place protection result in either low exposure or no exposure in the protected environment. Two-thirds of the scenarios examined result in exposures that would be expected to result in no observable effects. An additional 14.1% would be expected to result in exposures below the $LCt_{50}$ for newborn infants and still lead to observable effects. Only two scenarios tested result in expected exposures that exceed the $LCt_{50}$ for infants, do not exceed the $LCt_{50}$ for adult males.

Because the exposure categories are related to optimal protected exposure, the average exposure associated with being unprotected, remaining in the sheltered environment for the entire duration and vacating those shelters when the concentrations in the shelter exceed those outdoors (i.e., as the plume passes) have strong associations with the exposure categories. The average exposure reduction, among exposure categories resulting in an exposure, ranges from 59.0% to 74.0% over the length of the plume. This means that among the scenarios tested, in-place protection involving pressurization, enhancement or weatherization of seals and expedient measures reduces the exposure by more than half; however, in 8.2% of the scenarios examined the $LCt_{50}$ for newborn infants is exceeded, which means that lethal effects are likely.

Pressurized shelters (ACH = 0) result in no exposures or very low exposures in 86.7% of the scenarios examined, with an additional 8.9% of these scenarios resulting in expected exposures that result in observable effects. If pressurized shelter can be fully implemented prior to the plume's arrival, no exposures are expected. Expected exposures exceeding the $LCt_{50}$ levels for infants (2.2%) and adult males (2.2%) occur less frequently. Expedient shelter scenarios (ACH = 0.2), which also involve a slower implementation time, result in expected exposures below the observable level 73.3% of the time, with an additional 15.6% resulting in observable effects. The remainder (11.1%) exceed the $LCt_{50}$ for either infants (2.2%) or adult males (8.9%).

The scenarios are roughly equally distributed among those resulting in exposures exceeding the $LCt_{50}$ for either males or infants, those expected to result in observable effects, those resulting in exposures below the observable effects level, and no exposures, when wind speeds are slow (1 m/s). Under more rapid onset (winds of 3 or 6 m/s), the no-observable-effects category accounts for more than four of five scenarios, with only 3-m/s winds leading to exposures exceeding either the $LCt_{50}$ adult males or infants.

Roughly equal portions of those GB scenarios involving distances of 3 km exceed the $LCt_{50}$ (15.6% adult males, 4.4% infants), observable effects (35.5%), and having no observable effects (33.3%). The majority of scenarios for distances of 10 km and 20 km effectively reduce exposures to the no observable effects level (71.1% and 66.7% respectively). Only 4.4% of the scenarios examined result in expected exposures exceeding the 50% lethality level for adult males.

### 6.2.2 Nerve Agent VX Scenarios

Table 6.2 presents a descriptive summary of the results of the screening analysis for accident scenarios involving VX. Of the 135 goal-oriented emergency response scenarios examined involving VX, the expected exposures associated with less than 20% exceed the $LCt_{50}$ for any population segment and 8.1% exceed the $LCt_{50}$ for adult males under light activity. The average expected exposures in the protected environment are less than a fifth the expected exposures in the unprotected environment and can be as little as one-tenth of the unprotected exposures. The average expected exposures are reduced even further if the shelter can be vacated immediately upon the passage of the plume, but these further reductions are small. However, the reduced expected exposures on average remain seven times greater than the $LCt_{50}$ for adult males in 8.1% of the scenarios examined. It follows then that these in-place shelters, with exchange rates of 0, 0.2 and 0.5 ACH, reduce the exposure over the length of the plume by about three-fourths but are likely to fail to prevent deaths in 14.0% of the VX accident scenarios examined.

Most of the accidental releases of agent VX and the associated emergency response scenarios involving in-place protection result in either low exposure or no exposure in the protected environment. More than four-of-five scenarios examined result in expected exposures that would be expected to result in exposures below the $LCt_{50}$ for infants, with about half of the scenarios resulting in expected exposures below those where effects are observable.

The average exposure reduction, among exposure categories resulting in an exposure, ranges from 19.2% to 81.6% over the length of the plume. This means that among the scenarios tested, in-place protection involving pressurization, enhancement, or weatherization of seals and expedient measures reduces the exposure dramatically; however, in 14.0% of the VX scenarios examined, expected exposures are likely to exceed the $LCt_{50}$ for infants, thereby making lethal effects likely.

As with GB, pressurized shelters (ACH = 0) result in no exposures or very low exposures in a large proportion of the scenarios examined (71.1%), with an additional 22.2% of these scenarios resulting in observable effects. To the extent that pressurized shelters can be fully implemented prior to the plume's arrival, no exposures are expected. Expected exposures exceeding the $LCt_{50}$ levels for infants (4.4%) and adult males (2.2%) occur less frequently. Expedient shelter scenarios (ACH = 0.2), which also involve a slower implementation time, result in expected exposures below the observable level in 44.4% of the scenarios, with an additional 37.8% expected to result in observable but nonlethal effects. The remaining 17.8% of the scenarios examined would be expected to exceed the $LCt_{50}$ for either infants (6.7%) or adult males (11.1%). Enhanced shelters generally perform about the same as expedient measures, which seems to indicate a general trade-off between the time to implement expedient shelter, and the more immediate protection associated with enhanced shelter. In reality, enhanced shelter alone would be a unlikely recommendation; the outer barrier associated with enhancement would be augmented by expedient measures in a room within.

Again, the distribution of 1-m/s scenarios is fairly uniform across exposure categories for exposures exceeding the $LCt_{50}$ for either adult males or infants, those expected to

Table 6.2. Descriptive summary of results of goal-oriented screening analysis for scenarios involving VX and in-place shelter

| | E(exposure) greater than $LCt_{50}$ for adult male[a] | E (exposure) greater than $LCt_{50}$ infant[a] | E(exposure) greater than observed effects Ct[b] | E(exposure) less than observed effects Ct[b] | No exposure[c] |
|---|---|---|---|---|---|
| Scenarios | 11 | 9 | 44 | 56 | 15 |
| % of VX | 8.1 | 6.7 | 32.6 | 41.5 | 11.1 |
| | | Average exposure | | | |
| Unprotected, ($mg\text{-}min/m^3$) | 11,500 | 340 | 40 | 120 | 0 |
| In Shelter, ($mg\text{-}min/m^3$) | 2,350 | 40 | 4 | 0 | 30 |
| Vacated, ($mg\text{-}min/m^3$) | 150 | 20 | 3 | .02 | 0 |
| | | Average exposure reduction | | | |
| Overall, % | 81.6 | 68.5 | 58.3 | 79.2 | 0.0 |
| Relative, % | 89.7 | 76.4 | 68.1 | 85.7 | 0.0 |
| | | Response scenario | | | |
| ACH = 0[d], % | 2.2 | 4.4 | 22.2 | 60.0 | 11.1 |
| ACH = 0.2[d], % | 11.1 | 6.7 | 37.8 | 33.3 | 11.1 |
| ACH = 0.5[d], % | 11.1 | 8.9 | 37.8 | 31.1 | 11.1 |
| | | Meteorological conditions | | | |
| WS 1 m/s, % | 20.0 | 8.9 | 24.4 | 13.3 | 33.3 |
| WS 3 m/s, % | 4.4 | 6.7 | 40.0 | 48.9 | 0.0 |
| WS 6 m/s, % | 0.0 | 4.4 | 33.3 | 62.2 | 0.0 |
| | | Downwind distance | | | |
| 3 km, % | 20.0 | 15.6 | 55.6 | 8.9 | 0.0 |
| 10 km, % | 4.4 | 4.4 | 31.1 | 60.0 | 0.0 |
| 20 km, % | 0.0 | 0.0 | 11.1 | 55.6 | 33.3 |

[a]Expected exposure exceeds $LCt_{50}$ for males ("Adult M") and infants assuming light activity (see Tables 3.2 and 3.3).

[b]Expected exposure exceeds (greater than) or does not attain (less than) observed effects threshold for adults (see Tables 3.2 and 3.3).

[c]"No exposure" indicates that plume did not arrive in the first 3 h under the given condition.

[d]In-place shelters are characterized in terms of the air change rate (ACH), with 0 being pressurized shelters, 0.2 representing expedient shelters, and 0.5 representing enhanced shelters.

result in observable effects, those resulting in exposures below the observable effects level, and no exposures. Under more rapid onset (winds of 3 or 6 m/s), the no-observable-effects category accounts for 48.9% to 62.2% of the scenarios, with 3-m/s winds leading to exposures exceeding either the 50% lethality levels for adult males (4.4% and 0.0% respectively) or newborn infants (6.7% and 4.4% respectively).

VX scenarios involving 3-km distances are likely to result in fatalities among adult males (20.0%) and newborn infants (15.6%) in at least 35.6% of the scenarios examined. Observable effects are expected to result from more than half the scenarios screened, while less than 10% are characterized by no observable effects. Most scenarios for distances of 10 km and 20 km effectively reduce exposures to the no-observable-effects level (60.0 and 88.9% respectively). Only 4.4% of the scenarios examined result in expected exposures exceeding the $LCt_{50}$ for adult males, and all of these are for 10 km downwind.

### 6.2.3 Blister Agent Mustard (H/HD) Scenarios

A descriptive summary of the results of the screening analysis is presented in Table 6.3 for accident scenarios involving mustard. Of the 108 goal-oriented emergency response scenarios examined involving H, less than 20% of the expected exposures exceed the $LCt_{50}$ for newborn infants; 9.3% exceeded the $LCt_{50}$ for adult males under light activity; and 6.5% exceed the $LCt_{50}$ for newborn infants but not the $LCt_{50}$ for adult males. The average expected exposures in the protected environment are nearly one-fifth the expected exposures in the unprotected environment and can be more than 35 times smaller than the unprotected exposures depending on the exposure category. The average expected exposures are reduced even further if the shelter can be vacated immediately upon the passage of the plume, but these further reductions are modest. However, the reduced expected exposures on average remain 50 times greater than the $LCt_{50}$ for adult males in 9.3% of the scenarios examined.

Most of the accidental releases of agent H/HD and the associated emergency response scenarios involving in-place protection result in either low exposure or no exposure in the protected environment. More than 8% of the scenarios examined result in exposures below the $LCt_{50}$ for newborn infants. The average exposure reduction, among exposure categories resulting in an exposure, ranges from 59.3% to 82.3% over the length of the plume. This means that among the scenarios tested, in-place protection involving pressurization, enhancement, or weatherization of seals and expedient measures reduces the exposure dramatically; however, 15.8% of the H/HD scenarios examined result in expected exposures greater than the $LCt_{50}$ for infants, thus making lethal effects likely.

More than 80% of the scenarios involving pressurized shelter result in exposures below the $LCt_{50}$ for infants; nearly 75% of the enhanced scenarios and 67% of the expedient shelter scenarios had a similar result. Again if pressurized shelters are fully implemented prior to the plume's arrival, no exposures are expected. As with GB, pressurized shelters (ACH = 0) result in no or very low exposures in a large proportion of the scenarios examined (80.6%). Expected exposures exceeding the $LCt_{50}$ for infants (2.8%) and adult males (5.6%) occur less frequently. Expedient shelter scenarios (ACH = 0.2), which also

**Table 6.3. Descriptive summary of results of goal-oriented screening analysis for scenarios involving H/HD and in-place shelter**

| | E(exposure) greater than $LCt_{50}$ for adult male[a] | E (exposure) greater than $LCt_{50}$ infant[a] | E(exposure) greater than observed effects Ct[b] | E(exposure) less than observed effects Ct[b] | No exposure[c] |
|---|---|---|---|---|---|
| Scenarios | 10 | 7 | 79 | NA | 12 |
| % of H/HD | 9.3 | 6.5 | 73.1 | NA | 11.1 |
| | | **Average exposure** | | | |
| Unprotected, (mg-min/m$^3$) | 485,000 | 7,500 | 2,870 | NA | 0 |
| In Shelter, (mg-min/m$^3$) | 112,000 | 1,370 | 80 | NA | 0 |
| Vacated, (mg-min/m$^3$) | 81,000 | 1,100 | NA | 0 | |
| | | **Average exposure reduction** | | | |
| Overall, % | 82.3 | 59.3 | 74.6 | NA | 0.0 |
| Relative, % | 90.4 | 71.4 | 82.2 | NA | 0.0 |
| | | **Response scenario** | | | |
| ACH = 0[d], % | 5.6 | 2.8 | 80.6 | NA | 11.1 |
| ACH = 0.2[d], % | 11.1 | 5.6 | 72.2 | NA | 11.1 |
| ACH = 0.5[d], % | 11.1 | 11.1 | 66.7 | NA | 11.1 |
| | | **Meteorological conditions** | | | |
| WS 1 m/s, % | 22.2 | 2.8 | 41.7 | NA | 33.3 |
| WS 3 m/s, % | 5.6 | 11.1 | 83.3 | NA | 0.0 |
| WS 6 m/s, % | 0.0 | 5.6 | 94.4 | NA | 0.0 |
| | | **Downwind distance** | | | |
| 3 km, % | 22.2 | 13.9 | 63.9 | NA | 0.0 |
| 10 km, % | 5.6 | 5.6 | 88.9 | NA | 0.0 |
| 20 km, % | 0.0 | 0.0 | 66.7 | NA | 33.3 |

[a]Expected exposure exceeds $LCt_{50}$ for males and infants assuming light activity (see Tables 3.2 and 3.3).

[b]Expected exposure exceeds (greater than) or does not attain (less than) observed effects threshold for adults (see Tables 3.2 and 3.3).

[c]"No exposure" indicates that plume did not arrive in the first 3 h under the given condition.

[d]In-place shelters are characterized in terms of the air change rate (ACH), with 0 being pressurized shelters, 0.2 representing expedient shelters, and 0.5 representing enhanced shelters.

involve a slower implementation time, result in expected exposures below the $LCt_{50}$ in 72.2% of the scenarios. Enhanced shelters generally yield similar results as expedient measures, seemingly indicating a general trade-off between the time to implement expedient shelter and the more immediate protection associated with enhanced shelter.

The distribution of 1-m/s scenarios is characterized by exposures exceeding the $LCt_{50}$ for adult males 22.2% of the time; the $LCt_{50}$ for newborn infants is exceeded in 2.8% of the scenarios examined; and 41.7% of the scenarios would be likely to have observable effects. Note that because a plume travelling 1-m/s does not arrive at 20 km in 3 h 33.3% of the scenarios result in no exposure in this time frame. Under more rapid onset, (winds of 3 or 6 m/s) the observable effects category accounts for more than 80% of the scenarios. Scenarios involving 3 m/s winds lead to exposures exceeding the $LCt_{50}$ for adult males (5.6%) and newborn infants (11.1%). Faster winds of 6 m/s result in expected exposures larger than the $LCt_{50}$ for newborn infants in 5.6% of other scenarios examined.

Mustard gas scenarios involving 3-km distances exceed the $LCt_{50}$ for adult males and infants in 22.2% and 13.9% of the scenarios examined respectively. Observable effects are expected to result from 63.9% of the scenarios screened. The vast majority of scenarios for distances of 10 km and 20 km effectively reduce exposures to below the $LCt_{50}$ for adult males and infants (88.9 and 100%, respectively). Only 5.6% of the scenarios examined result in expected exposures that exceed the $LCt_{50}$ for adult males, and another 5.6% result in exposures above the $LCt_{50}$ for infants; furthermore, all of these are at distances of 10 km.

## 6.3 ANALYSIS OF SELECTED SCENARIOS

The same goal-oriented emergency response scenarios found in the screening analysis are discussed throughout this section. Again, the scenarios are considered goal oriented because they postulate system parameters consistent with a state-of-the-art emergency response system. First, these emergency response scenarios assume that the hazard can be detected and assessed and that a decision to warn the public can be made in 5 min. Second, it is assumed that a combination warning system, using sirens for outdoor warning and a telephone ring-down system for indoor warning, will be implemented. The third assumption is that the public will respond similarly to that in the Confluence, Pennsylvania, train derailment, but at a rate that is 25% faster. Fourth, implementation of pressurized and enhanced shelters are assumed to involve closing doors and windows, while expedient measures are assumed to involve closing doors and windows, and taping and sealing a room within. Finally, passive implementation of enhanced alternatives assumes that being indoors achieves a measure of protection and thereby initiates the probability of having completed the implementation by the probability of being indoors at the time of the accident. No passive augmentation with respect to expedient shelter is possible because the activities require direct participation by the people to be protected. The implications associated with these assumptions are summarized in terms of the joint probability of having implemented the given action in Fig. 6.1.

The largest release of GB under moderate onset of 3 m/s exemplifies an extreme case where large releases are dispersed fairly quickly to locations in close proximity.

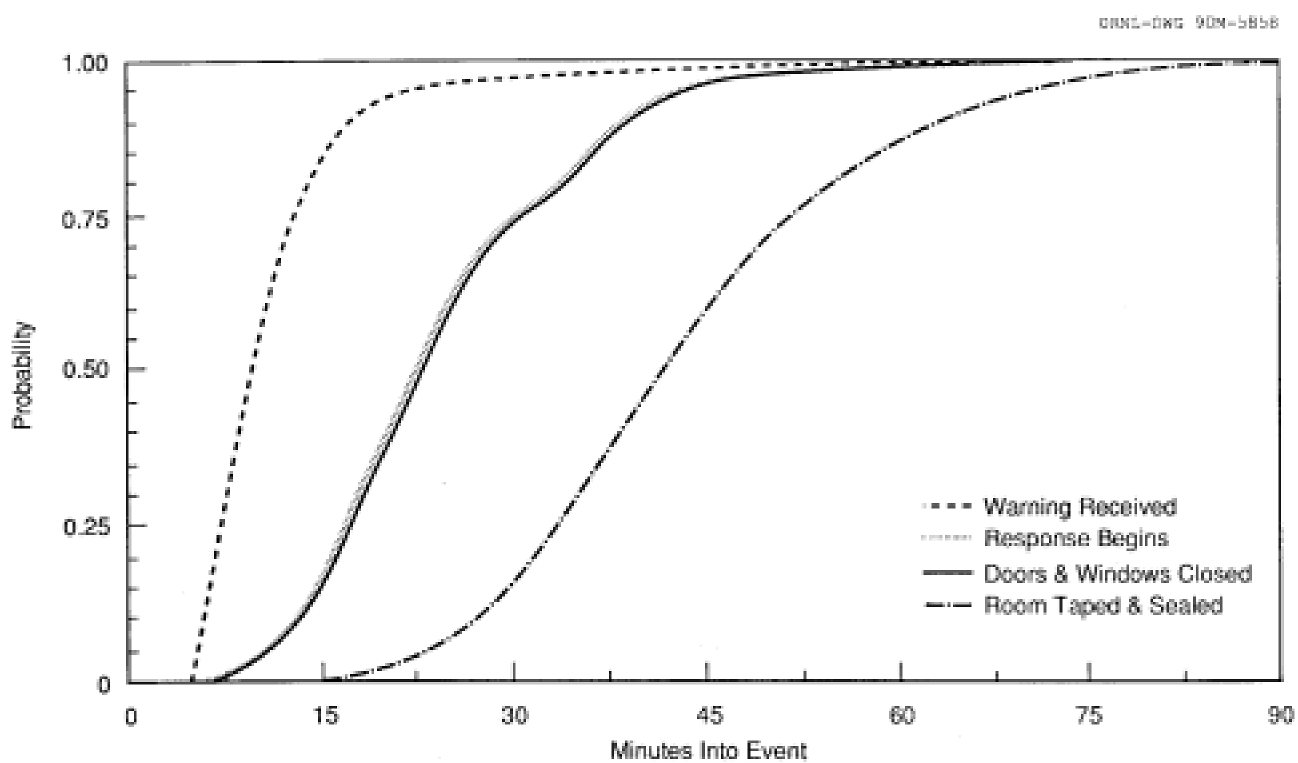


**Fig. 6.1. Probability of completing in-place protection activities by time into the event.**

Under these accident conditions, the plume arrives at a 3-km distance from the source point in about 17 min (Fig. 6.2). At this time into the accident, only a small proportion of people are expected to have completed the implementation of expedient shelters (Fig. 6.1), while the probability of completing the activities associated with enhanced shelter is just under 0.5. Hence, for in-place shelters to be effective, rapid emergency response is critical.

The lowest exposure achievable with a shelter system characterized by any exchange rate is typified by ideal protection, which reduces the expected exposure to the structural limit or the exposure reduction capacity. Such an ideal system assumes that all people will implement the action before the arrival of the plume and vacate the shelter at the optimal time. In an ideal system with an exchange rate of 0.5 ACH, the expected exposures would remain below the $LCt_{50}$ for infants but would probably result in observable effects for many people. However, getting people into these shelters before the arrival of the plume does not provide adequate protection. Failing to vacate these enhanced shelters results in expected exposures that exceed the $LCt_{50}$ for adult males a little over an hour after the leading edge of the plume arrives (Cf. Appendix I). This finding underscores the system requirement to notify people in the shelter when the plume has passed. The area between the two forks in Fig. 6.2 graphically illustrates the minimum expected exposure when people vacate the shelter immediately when the concentration inside exceeds the concentration outside and the maximum expected exposure associated with staying in the shelter for the entire time.

When the probability of implementing the action is considered under this large moderate-onset accident scenario, the exposure inside the shelter is expected to exceed the $LCt_{50}$ for adult males (light activity) by the time the plume has passed; again, this assumes that people are protected by an enhanced shelter characterized by a 0.5 ACH exchange rate. The action would fail to prevent deaths even if an all-clear signal gets people to vacate the shelter as soon as the plume has passed. More problematic, however, is the potential to contribute to the potential harm by continuing to accumulate exposure as the agent within the shelter is replaced with the relatively fresh air in the unprotected environment outside.

The trade-off between reductions in air changes and the amount of time to achieve those reductions is evident in the comparison of the expected exposures associated with the enhanced shelter (0.5 ACH) and the expedient shelter (0.2 ACH). The expedient shelter reaches higher levels of exposure than the enhanced shelter as a direct result of the longer implementation time, but enhanced shelters are accumulating exposure faster in the protected environment. For those people implementing the procedures before the arrival of the plume, the protection is inversely related to the air exchange rate between the protected and unprotected environments. Putting people in pressurized shelters would fail to eliminate exposure because of the exposure acquired before completion of the implementation of the action. As a result, even given the excellent protection afforded by pressurized shelters, implementation (involving closing the doors and windows and turning off heating, cooling, and circulation systems) results in an expected exposure just slightly below the $LCt_{50}$ for adult males. In this instance, the behavioral/organizational system of emergency response constrains the amount of protection afforded by a pressurized shelter.

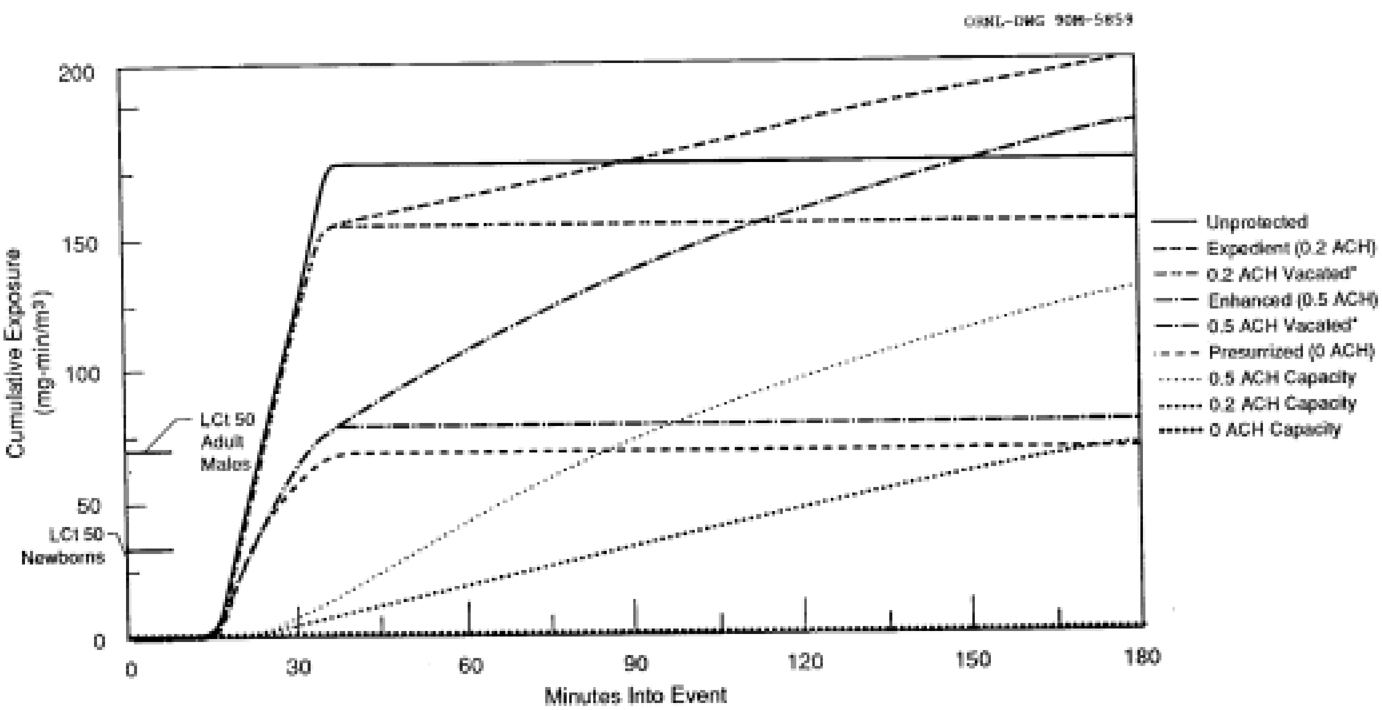


**Fig. 6.2. In-place shelter scenarios at 3-km distance for GB class V events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr. *Exposure curve is flat after the plume passes because the shelter is vacated when the concentration outside is less than that inside.

Figure 6.3 presents alternatives for in-place protection of people at 3 km for a large release of VX under moderate onset (wind 3 m/s). Again, the response scenario is characterized by the goal-oriented emergency response system as summarized in Fig. 6.1. The ideal response summarized by the exposure reduction capacity of an expedient shelter alternative characterized by an exchange rate of 0.2 ACH constrains expected exposure to levels below the $LCt_{50}$ for infants. Hence, protection levels can be quite good for people who are fortunate enough to receive a warning, decide to respond, and complete the implementation of the required activities before the arrival of the plume. To attain maximum protection afforded under this system, the shelters will have to be vacated once the plume has passed.

Taking the probability of completing implementation into account results in about a threefold increase in the expected exposure. While the expected exposures remain below the $LCt_{50}$ for adult males (light activity) during the first 3 h, remaining in the shelter beyond about 2.5 h results in exposures greater than those in unprotected environments for the occupants. Vacating the shelter as soon as the concentration of agent in the unprotected environment is lower than the concentration in the shelter results in an ending exposure of about 20 mg-min/m$^3$.

Because the structural capacity of an in-place shelter characterized by 0.5 ACH allows more air into the shelter, the exposure reduction capacity is not a low as the exposure reduction capacity of the shelter characterized by 0.2 ACH. The ideal protection curves, whether vacated or remaining in the shelter for the entire duration, represent greater exposures than would be allowed with a tighter seal. However, because it takes longer to implement the taping and sealing that results in the reduced air exchange, the enhanced (0.5 ACH) shelter gives greater protection when response time is considered. If the enhanced shelter can be vacated as soon as the concentration of agents is smaller outside the shelter, the exposures can be anticipated to remain slightly below the 50% lethality level for infants.

Pressurizing the shelters means that the expected exposure is strictly a function of emergency response, specifically the joint probability of implementing the action. Pressurized shelters are equivalent to having no contaminated air penetrate from the unprotected environment to the protected shelter (i.e., an air exchange of 0 ACH). Pressurized shelters maintain the expected level of exposure below the $LCt_{50}$ of newborn infants. Furthermore, because there is no penetration of agent into the pressurized shelter, vacating the protected environment is not required until or unless the filtration capacity of the system is exceeded. This capacity depends on the number of filters and their individual ability to absorb agent.

Under slower onset scenarios, emergency response achieves nearly complete response, which minimizes the difference between the ideal protection achieved when exposure reduction capacity is reached. This reflects the increased probability of implementing the action associated with more time available to respond. Figure 6.4 illustrates a slow onset (winds of 1 m/s) of a small release of GB 3 km downwind. Because of the slower onset, the behavioral difference between expedient and enhanced protection is minimized, which means the ability to protect for each system is primarily a function of the air exchange rate. Under these circumstances, the highest air exchange rate examined (0.5 ACH) results in expected exposures below the $LCt_{50}$ for newborn

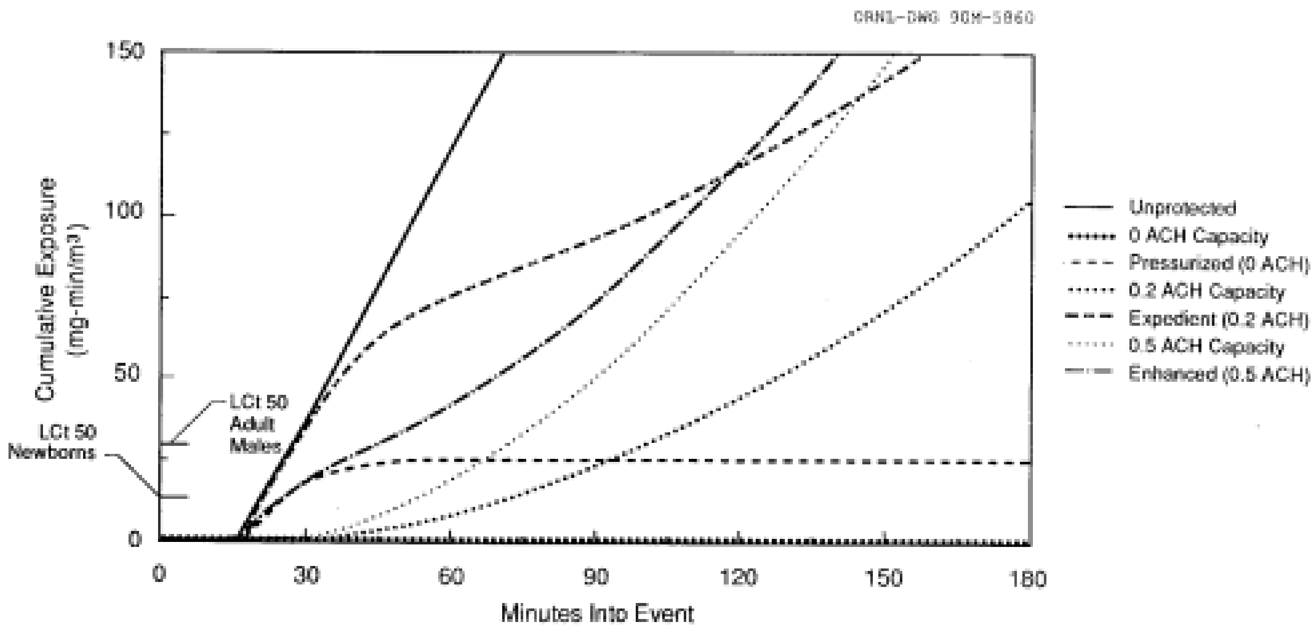


**Fig. 6.3. In-place shelter scenarios at 3-km distance for VX class V events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr. Because the release continues for the duration of the first three hours, no shelter is vacated.

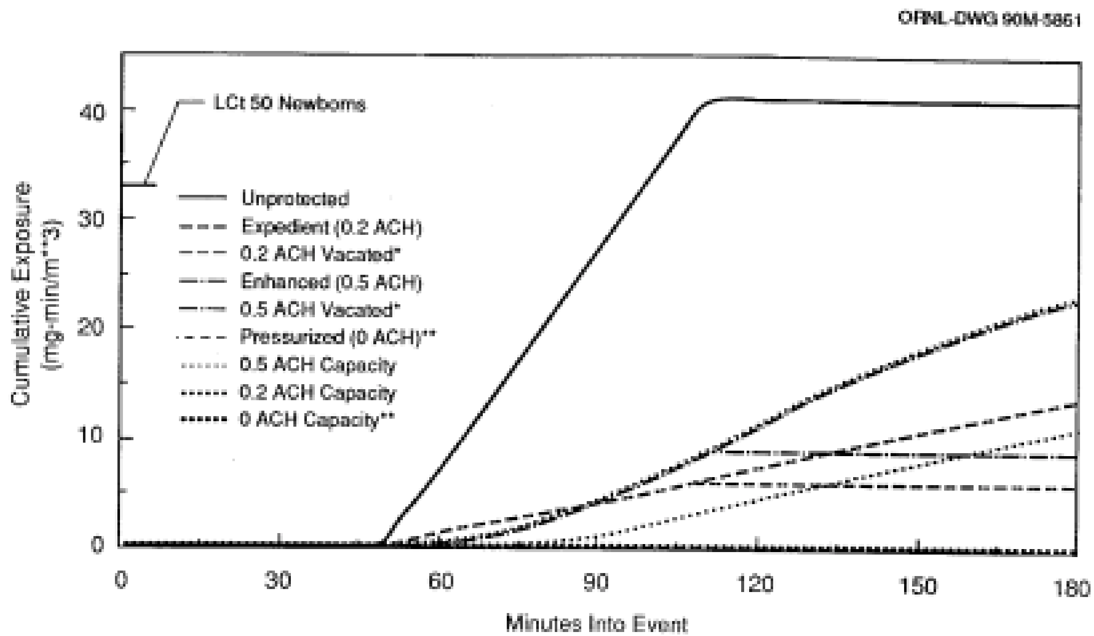


**Fig. 6.4. In-place shelter scenarios at 3-km distance for GB class I events when 1-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr. *Exposure curve is flat once the plume passes because the shelter is vacated once the concentration outside is less than that inside. **Because the activities to implement pressurized shelters are nearly complete when the plume arrives, the expected exposure and capacity are indistinguishable on the x-axis.

infants. As could be anticipated, the lower the air exchange rate, the better the ability to protect, with pressurization providing maximum protection for this scenario.

The increased time to respond alone is not sufficient to provide protection from larger releases. Figure 6.5 presents the same in-place protection alternatives for a moderate-sized release of VX. While the overall pattern of protection is the same, the resulting expected exposures exceed the $LCt_{50}$ for adult males under the enhanced and expedient shelter alternatives. Finally, pressurized shelters clearly provide maximum protection from slow onset releases as long as the filtration system removes the contaminants from the air, but even here the $LCt_{50}$ for newborn infants is nearly reached.

Figure 6.6 illustrates in-place protection alternatives for continuous releases over extended periods. Implementing an enhanced shelter (0.5 ACH) in a goal-oriented emergency response system achieves more than three-fourths of the protection available in the system; however, within 40 min of the arrival of the plume, the expected exposure exceeds the 50% lethality level for adult males. By the end of the first 3 h, when the unprotected exposure is nearly three orders of magnitude above the 50% lethality exposure, the protected exposure is more than 300 times the 50% lethality exposure for adult males. Because of the probability of completing the implementation of pressurized shelters, which involves closing doors and windows and turning off central circulating systems, the pressurized system maintains the expected exposure at about the 50% lethality level for adult males. On the other extreme, because of the slower implementation of expedient shelters, which involves taping and sealing a room as well as closing doors and windows, a greater exposure is expected before implementation by all people in the area. This additional time to completely implement the protection leads to an expected exposure above what would be expected in enhanced shelters.

## 6.4 IN-PLACE PROTECTION CONCLUSIONS

When situations characterized by adverse health effects are anticipated, evacuation of an area is preferable to in-place shelter when it can be completed before impact. The preference for evacuation is based on two fundamental characteristics of in-place sheltering contrasted with evacuation. First, while a portion of the exposure continues after implementation of in-place shelters, exposure is avoided completely by evacuation. Second, shelters that reduce but do not eliminate infiltration of toxic agents will have to be vacated once the plume has passed to afford maximum protection, but no second step is required after evacuation. Shelters that reduce infiltration of toxics also can increase the expected exposure in the sheltered environment if they are not vacated when the plume passes. For example, plumes that would not be expected to exceed the $LCt_{50}$ for a population can be augmented by slow implementation and improper ventilation of the shelter upon the passage of the plume.

It follows then that in-place protection characterized by reduced infiltration provide limited protection in long duration events. This arises because of the character of the exchange rate that simply allows a portion of what is in the unprotected environment into the sheltered environment. Hence, over long duration releases, in-place shelters downwind will continue to accumulate exposure, under these conditions even fairly small concentrations of agent can augment significantly over relatively short durations. For

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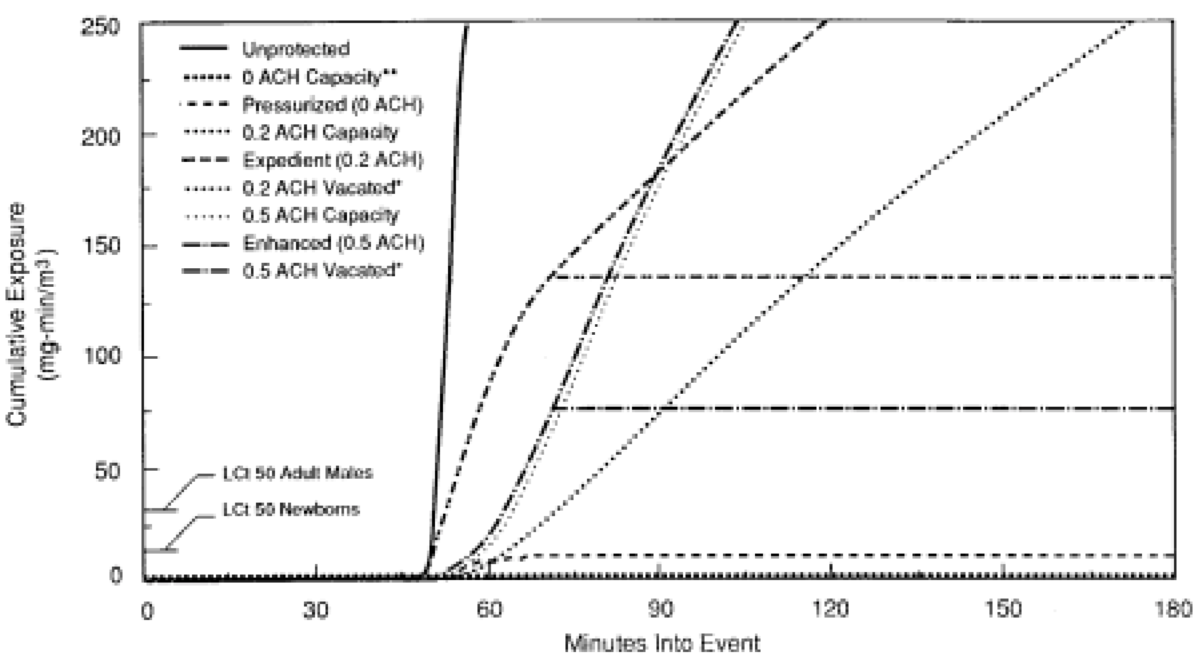


**Fig. 6.5. In-place shelter scenarios at 3-km distance for VX class III events when 1-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr. *Exposure curve is flat after the plume passes because the shelter is vacated when the concentration outside is less than that inside. **Because pressurized shelters completely eliminate exposure, capacity rests on the x-axis.

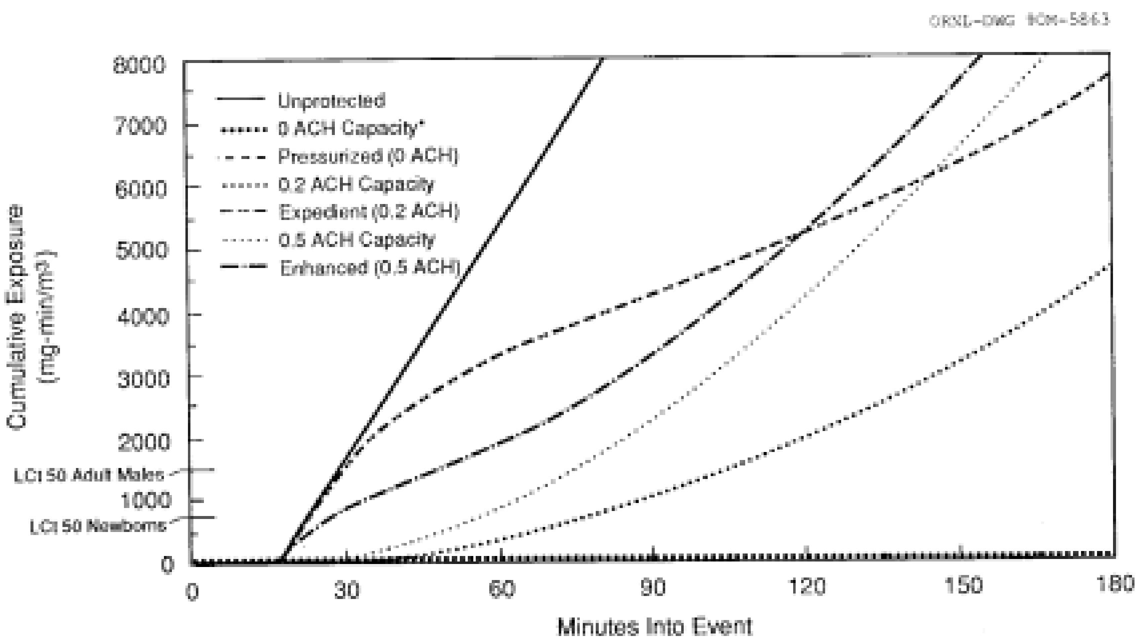


**Fig. 6.6. In-place shelter scenarios at 3-km distance for H/HD class V events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr. Because the release continues for the duration of the first 3 hr, no shelter is vacated. *Pressurized capacity rests on x-axis.

example, consider a continuous release of VX that results in 300 mg-min/$m^3$ being released each hour; this amounts to exposures of 5 mg/$m^3$ each minute in the unprotected environment, which reaches the $LCt_{50}$ for adult males in less than 15 min; but in a shelter characterized by a 0.5 ACH exchange rate, the $LCt_{50}$ for newborn infants would be reached in about 4 h. Hence, in-place shelters characterized by 0.5 ACH exchange rate can be recommended in response to small releases for relatively short durations. Larger releases (exceeding 5 mg/$m^3$ per minute) or those with unknown or long durations should avoid exposure via evacuation if possible.

It is inappropriate to recommend enhanced shelters alone, because of the additional protection afforded by implementing expedient measures within enhanced shelters. It is much more effective to take advantage of the rapid implementation of enhanced shelters and to augment them with the reduced infiltration of expedient shelter procedures for an interior room. This approach to protection in-place affords a moderate degree of protection quickly and can be followed by a higher level of protection upon completion of the taping and sealing of the interior room. Hence, by curtailing exposure early in the period through rapid implementation, and by limiting continued exposure later in the emergency due to the reduced infiltration associated with taping and sealing an interior room, a combined method provides optimum protection among the in-place measures that allow infiltration to continue (i.e., non-pressurized shelters).

# 7. EVALUATING INDIVIDUAL RESPIRATORY PROTECTION

This section describes the analysis of respiratory protection as a protective measure that avoids exposure for most people wearing the devices. This section first considers the concept of respiratory protection in terms of existing standards for devices, and in terms of constraints associated with their use, which completes the model development; the section continues with the preliminary analysis in terms of a screening analysis, and then a closer examination of selected scenarios. The section ends with some preliminary conclusions concerning the use of respiratory protection in chemical agent emergencies.

## 7.1 RESPIRATORY PROTECTION CONCEPTS

Individual respiratory protection involves the removal of agent before inhalation through the use of filtration devices. Respiratory devices that are specifically designed for use in chemical environments are characterized generally by the degree of leakage around the device or seal and the amount of agent that can be absorbed before the filter capacity is exceeded. The two characteristics are referred to as leakage and breakthrough capacity, respectively.

Expedient respiratory protection, such as a folded handkerchief or towel, has short-term utility when no other respiratory protection device is available. Tests with aerosols have demonstrated aerosol removal efficiencies of greater than 85% upon inhalation through eight thicknesses of a cotton (man's) handkerchief or two thicknesses of bath towels (Guyton, et al. 1959). No significant increase in removal efficiency was observed when these items were dampened and tested. Greater thicknesses of handkerchief increased breathing resistance to intolerable levels (i.e., 36 mm $H_2O$; acceptable levels approximate 15 to 20 mm $H_2O$) (Guyton, et al. 1959). Such expedient measures would provide reasonable short-term inhalation protection from aerosols/droplets of VX or mustard, but not from GB or GA vapor. Respirators provide excellent protection from inhalation exposure to both aerosols and vapor. As a result, this analysis evaluates respirators only.

Respirators include a face-piece assembly fitted with filters to remove airborne toxic compounds. They do not supply air and are not intended for use in an oxygen-deficient atmosphere. Available face-piece designs provide varying degrees of protection to the eyes, face, and respiratory organs/tissues. A full-face design is evaluated in this analysis. Other types of respiratory protection are described in Sect. C.3 (Appendix C).

Filter elements are packed with activated charcoal that has been impregnated with salts of copper, silver, and/or chromium to augment the capacity of the filter to absorb or denature chemical agents. Filter capacity is largely a function of storage conditions and regular maintenance/replacement of filter elements.

### 7.1.1 Respiratory Standards for Breakthrough Capacity

Two principal standards govern respirator filter sorption capacity for chemical warfare agents: those established by the North Atlantic Treaty Organization (NATO) for

civilian respirator units (NATO 1983) and those published by the U.S. Army Armament Research and Development Command at the Aberdeen Proving Ground (U.S. Department of the Army 1983). The NATO civilian standards require that a respirator protect the wearer from the toxic effects of two exposures to nonpersistent nerve agents (i.e., GA or GB) at a Ct of 1500 mg-min/m$^3$ each (i.e., a total of 3000 mg-min/m$^3$) or from vapor exposure to a persistent agent (i.e., VX or any vesicant agent) at a Ct of 1000 mg-min/m$^3$ (NATO 1983). This standard has not been accepted wholly by NATO member states because European battlefields are likely to be close to major population centers, and potentially exposed civilians using respirators with the stated design specifications would receive much less protection than military personnel in adjacent combat zones. Standard, U.S. military-issue, full-face (i.e., M17A1/M17A2) masks equipped with filter elements specifically designed to remove nerve and mustard agents protect the wearer from the toxic effects of exposure to chemical warfare agents at a Ct of 159,000 mg-min/m$^3$ (U.S. Department of the Army, Armament Research and Development Command 1983). These standards are considered breakthrough values (i.e., the Ct at which the filter capacity is exceeded and the wearer begins to inhale air containing ambient concentrations of agent). An example M17-series mask and filter are depicted in Fig. 7.1. This analysis compares the protection offered by NATO civilian-standard respirators with U.S. military-issue (i.e., M17A1/M17A2) respirators or other respiratory devices equipped with filter canisters of the same sorptive capacity.

### 7.1.2 Problem Areas and Limitations

The NATO Civil Defense Committee considers respirators to be "the single most effective means of protection against chemical agents" (NATO 1983). Nevertheless, the utility of the unit and the degree of protection obtained are limited by several physical factors:

1. training,
2. integrity of mask-to-face seal,
3. storage conditions, and
4. visual clarity.

The Delphi Panel concluded that respirators could be an effective means of protection but would be limited for civilian populations by a number of social and logistic factors:

1. an individual's ability to find the respirator,
2. individual collocation with the respirator at the time of a release,
3. access to an adequate number of respirators to protect the potentially exposed population, and
4. equipment maintenance.

To be most effective, each respirator user should be fitted and tested with an appropriately sized mask and should receive training in the proper donning procedure and

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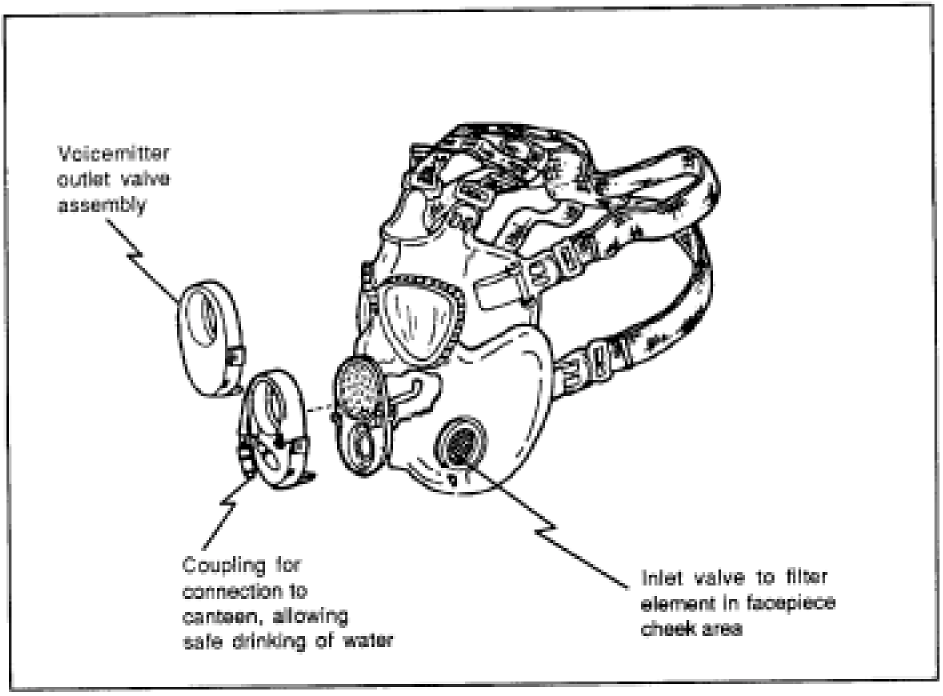


**Fig. 7.1. Exploded view of U.S. issue standard M17 series mask for troop protection from chemical/biological agent exposure.** See U.S. Department of the Army, Headquarters, *Operator's Manual for Mask*, TM 3-4240-279-10, Chemical Biological: Field, 1987.

in the use and care of the device (fitting and testing standards are summarized in ANSI 1982). NATO assumes that a trained, able-bodied person can don and begin using a respirator in 15 s; the Army assumes 9 s for this procedure. "Green" military recruits usually require 2 to 4 h of training to achieve this level of expertise. Yearly refresher training is considered essential to maintain rapid response for normal preparedness; it is recommended that respirator training for emergencies be repeated every 3 months to ensure maintenance of rapid response (B. Reinert, Personnel Protective Studies Division, Los Alamos National Laboratory, Los Alamos, New Mexico; personal communications to C. Griffith, Energy Division, ORNL, July 26 and October 20, 1989). The current analysis assumes an implementation period of 2 min to retrieve the device from its storage location and don the respirator.

The integrity of the mask-to-face seal can be compromised by the presence of facial hair (beards, and sideburns), face sizes that are outside the range for which the respirators are designed, facial abnormalities, wrinkled or scarred skin, and absence of teeth. Some data regarding the size of the U.S. population potentially characterized by these factors are included in Tables 7.1 through 7.3. A summary of surveys performed by The Roper Organization (and provided to the Roper Center for Public Opinion Research) and "best-guess" data provided during interviews with representatives of the National Cosmetological Association and the National Association of Barber Styling Schools is presented in Table 7.1. Beards, estimated to be worn by 7.1% of the total population (summed frequencies of "beard only" and "mustache and beard" from the Roper Survey; supported by the annual averages of 9 to 10% and 7.5% estimated by the National Cosmetological Association and the National Association of Barber Styling Schools, respectively), are the facial hair patterns deemed most likely to interfere with the mask seal. Mustaches, low hairlines or bangs are considered less likely to compromise the seal, although any form of facial hair that covers potentially masked areas should be removed to ensure a good mask-to-face seal. Recent safety regulations established by the U.S. Army Material Command state that "the wearer's face will be clean shaven to the extent that there is no possible interference of any facial hair growth (beard, and sideburns) with the sealing surfaces of the protective mask. . ." (U.S. Department of the Army 1987). Of course, respiratory devices that do not use those skin surfaces to attain a seal (e.g., hoods, mouthpiece respirators) are not affected. Unfortunately, such requirements are likely to meet with varying degrees of acceptance by the public. Certain types of facial hair (particularly mustaches) also may interfere with the proper function of respirator valves and should be removed prior to respirator use if at all possible. The integrity of the seal of respiratory devices can be ensured for soldiers and chemical workers when consent to such requirements is implicit, but meeting these requirements is strictly voluntary for the public.

There are three standard mask sizes of M17A1 respirators (S, M, and L) and four sizes of M17A2 respirators (S, M, and L, as well as an "X-SMALL" design to fit lighter, shorter, female recruits) (U.S. Department of the Army Headquarters 1987). There are no child-sized M17 respirators, although the Swedish civil defense authorities have developed face masks for children in seven different sizes (personal communication; B. Reinert, Personnel Protective Studies Division, Los Alamos National Laboratory, to C. Griffith, Energy Division, ORNL, July 26, 1989). Some data characterizing the undersized portion of the U.S. adult population (who would be considered difficult to fit

Table 7.1. Frequency of facial hair among U.S. males

| Source | Facial hair pattern | Proportion of males queried (%) | Proportion of total population queried (%) |
|---|---|---|---|
| 1983 Roper Survey[a] | Mustache only | 28 | 13.2 |
| | Beard only | 1 | 0.5 |
| | Mustache and beard | 14 | 6.6 |
| | No facial hair | 54 | 25.4 |
| National Cosmetological Association[b] | Some facial hair (annual average) | 18–20 | 9–10 |
| National Association of Barber Styling Schools[c] | Some facial hair (winter) | 20 | 10 |
| | Some facial hair (summer) | 10 | 5 |

[a]The Roper Center for Public Opinion Research, 1983. *Roper Reports* 83-10, New York.

[b]Best guess; E. Roach, Member, National Cosmetological Association, St. Louis, personal communication to C. Griffith, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 4, 1989.

[c]Best guess; J. Stone, President, National Association of Barber Styling Schools, Lincoln, Nebraska; personal communication to C. Griffith, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 26, 1989.

**Table 7.2. Proportion of insured U.S. adults who are below military standard weight[a]**

| Sex/age | Total Policies | Below weight standard (%) | Total |
|---|---|---|---|
| Males | 3,980,096 | 2.6 | 102,135 |
| 17–19 | 62,259 | 12.0 | 7,471 |
| 20–29 | 846,931 | 4.0 | 33,877 |
| 30–39 | 1,448,084 | 2.1 | 30,410 |
| 40–49 | 1,147,589 | 2.0 | 22,952 |
| 50–59 | 415,824 | 1.5 | 6,237 |
| 60–69 | 59,409 | 2.0 | 1,188 |
| Female | 588,819 | 12.5 | 73,443 |
| 17–19 | 17,790 | 34.4 | 6,120 |
| 20–29 | 88,706 | 5.2 | 4,613 |
| 30–39 | 120,810 | 22.7 | 27,424 |
| 40–49 | 222,149 | 10.7 | 23,770 |
| 50–59 | 117,133 | 8.2 | 9,605 |
| 60–69 | 22,231 | 8.6 | 1,912 |
| Total | 4,568,915 | 3.8% | 175,578 |

[a]Includes people who are at or below weight standard regardless of height.

*Source: The 1979 Build Study*, jointly sponsored by Society of Actuaries and the Association of Life Insurance Medical Directors (Provided through the courtesy of Frank S. Irish, Senior Vice President and Corporate Actuary, John Hancock Mutual Life Insurance Company, July 7, 1989).

Table 7.3. U.S. eyeglass wearing patterns by type of eyewear and year[a]

| Year | Millions of Individuals (% of total population) | | | |
|---|---|---|---|---|
| | Non-wearing | Eyeglass only | Eyeglass with contacts | Total eyeglass wearers |
| 1979 | 92.32 (41.4) | 116.7 (52.4) | 13.89 (6.2) | 222.91 (58.6) |
| 1981 | 94.86 (41.7) | 114.26 (50.2) | 18.37 (8.1) | 227.49 (58.3) |
| 1983 | 95.25 (41.0) | 114.30 (49.3) | 22.49 (9.7) | 232.04 (59.0) |
| 1985 | 97.42 (41.1) | 115.22 (48.6) | 24.40 (10.3) | 237.04 (58.9) |
| 1987 | 99.65 (41.4) | 118.61 (49.3) | 22.44 (9.3) | 240.70 (58.60) |

[a]National Consumer Eyewear Study (1988) performed by Optical Manufacturers Association. (Provided through the courtesy of Gregory Mankevich-Koziol, Director of Government Relations, Optical Manufacturers Association, July 24, 1989.)

with an appropriately sized respirator) are available from a build study commissioned by the Society of Actuaries and the Association of Life Insurance Medical Directors (1979; see Table 7.2). If the U.S. adult population that has insurance policies is assumed to be similar to the entire U.S. population in all other respects, approximately 3.8% would be sufficiently underweight to make respirator fitting problematic. This estimate is composed of 2.6% of the adult male population between 17 and 69 years plus 12.5% of the adult female population in the same age class. Facial abnormalities such as hollow temples, a high nose, protruding cheekbones, and deep wrinkles or scars as well as absence of some or all teeth also can compromise the respirator seal. Recent estimates of the numbers of individuals wearing dentures range between 7 and 8.7% of the U.S. population (J. Brown, National Center for Health Statistics, Hyattsville, Maryland personal communication to C. Griffith, Energy Division, ORNL, July 20, 1989). The current analysis assumes that 15% of the people using respiratory devices will experience poor fit conditions from all causes (leakage = 0.15).

The importance of suitable storage conditions for respirators is often overlooked. The filter and seals can deteriorate with time, particularly if stored in a humid environment. A few months' open storage at 80% RH is sufficient to reduce the sorptive capacity of an activated charcoal filter by 50% (Briefing sheets provided by W. K. Davis, Physical Protection Directorate, CRDEC, Aberdeen Proving Ground, Maryland, to C. V. Chester, Oak Ridge National Laboratory, Energy Division, March 9, 1987). The Army Material Command requires that "the protective masks will be stored so they will not be exposed to sunlight, heat, extreme cold, moisture, or any other environment which might cause deterioration" (U.S. Department of the Army 1987). Further, ANSI guidelines caution against "excessive moisture, or damaging chemicals" and distortion of "elastomeric parts" (ANSI 1981). Clearly, respirators will need to be stored in moisture- and dust-proof packaging at convenient, but protected, locations.

Even so, the U.S. Department of the Army requires periodic filter element replacement to ensure maximum filter capacity and update unit certification. Under peacetime conditions and in temperate climates, the mandatory filter element replacement interval is 12 months; in tropical climates, the replacement interval is compressed to a mere 2 months (U.S. Department of the Army Headquarters 1987). If the unit has been immersed in water or if the filter elements have been crushed or otherwise compromised, replacement is also necessary (U.S. Department of the Army Headquarters 1987).

Clear vision while wearing respirators is essential to fulfilling the requirements of other protective actions, such as self-transport to mass shelters, implementing expedient shelter activities, or evacuation. Individuals requiring corrective lenses will not be able to wear them with a respirator (U.S. Department of the Army 1987; U.S. Department of the Army 1989a,b; ANSI 1981); eyeglass temple pieces that pass between the sealing surface of the respirator face-piece and the wearer's face interfere with the seal, while contact lenses may absorb/retain trace quantities of agent or other foreign material that could irritate or blind the eye after the respirator is put on and when the wearer cannot remove the offending lenses. As a temporary measure, eyeglass temple pieces can be removed and the spectacles and frame taped to the wearer's face. Fitted, prescription optical inserts can be made readily available to those who need them; these inserts would, of course, require pre-installation. Accommodating corrective lens users is likely to be a very common problem in providing respirators to the public. The number of corrective lens wearers is sizable; successive surveys taken by the Optical Manufacturer's Association since 1979 indicate that approximately 60% of the U.S. population regularly wears eyeglasses or eyeglasses with contact lenses (see Table 7.3). These use estimates include those who merely require corrective lenses when reading or performing other close work.

## 7.2 SCREENING ANALYSIS

Two respiratory protection scenarios were evaluated for the 14 release scenarios summarized in Table 4.2 for three downwind distances (3 km, 10 km, and 20 km) and three meteorological conditions (winds of 1, 3, and 6 m/s with stability classes F, D, and C, respectively). A total of 252 release/response scenarios resulted. The response scenarios examined herein are considered "goal oriented" because they are consistent with a state-of-the-art emergency response system. Such a system can provide for (1) a

decision to warn that is made within 5 min of the accident, (2) a combination warning system using warning sirens outdoors and a telephone ringdown system indoors, (3) a public response 25% faster than that observed in the Confluence, Pennsylvania, train derailment, and (4) 15% of the respirators used by the public under self-donned conditions will leak around the filter. The efficiency of individual respiratory units fitted with two different filter elements was compared: the NATO civilian vapor standard for GA/GB at 3000 mg-min/$m^3$ and VX/vesicant at 1000 mg-min/$m^3$ (NATO 1983), and the U.S. military M17A1/M17A2 respirator filter standard of 159,000 mg-min/$m^3$ (U.S. Army Armament Research and Development Command 1983).

In general, the following analysis assumes reasonably good implementation conditions in that full-face respirators are used by adults. Other options could be examined if individual respiratory protection for toddlers and/or infants needs appraisal. Currently, several hood jacket and infant carrier designs equipped with battery-driven or passive filters are commercially available (see Fig. C.2 from Appendix C); several are recommended by the Swedish Civil Defense Administration. Additional engineering data would need to be provided by the manufacturer before these designs could be evaluated in the same manner as M17A1/M17A2 respirators.

Assuming that 15% of the respiratory devices used will leak around the filter at the seal may underestimate the protective capacity of respiratory devices. This occurs because civilians faced with a chemical emergency, where respirator use is critical, would be likely to do without eyeglasses and make numerous other expedient decisions to improve face-piece fit the portion experiences leakage may be smaller than 15%. Expedient hood designs also may be employed in conjunction with respirator use. Derringer et al. (1987) found that an $M_4$ bubble periphery mask exhibited the best performance of all mask concepts tested, with a 87.2% pass rate (plus or minus 5%) in self-fitted tests. Hughes et al. (1988) found that various designs of the XM40 mask provide self-fit pass rates of 88 to 97%, depending on the amount of supervision and the existence of a hood; however, the use of spectacles significantly reduced the ability of these masks to protect the wearer. Authors concluded that combat spectacles cannot be worn if the safety standards associated with the Joint Services Operational Requirements are to be met. Moreover, respiratory devices that leak 15% of the time would be unlikely to be recommended for public use as part of an effective emergency response program.

### 7.2.1 Nerve Agent GB Scenarios

A descriptive summary of the screening analysis results for respirator use under the selected GB release scenarios is presented in Table 7.4. Of the 90 GB scenarios, 11.1% (n = 10) resulted in expected exposures that exceed the estimated $LCt_{50}$ for either adult males or infants (see Table 3.3). Three-fourths of the high-exposure release scenarios are the result of a GB class V release, and the other 25% result from GB class IV accidents. These large result in exposures exceeding the $LCt_{50}$ for adult males. Both of the respiratory response scenarios resulting in expected exposures greater than the $LCt_{50}$ for newborn infants but not exceeding the $LCt_{50}$ for adult males arise from GB class III accidents. Scenarios resulting in expected exposures below the $LCt_{50}$ for infants are distributed among all accident classes; all except GB Class I scenarios resulted in exposures

Table 7.4. Descriptive summary of screening analysis results for scenarios involving GB and respiratory protection

| | E(exposure) greater than $LCt_{50}$ for adult males[a] | E(exposure) greater than infant $LCt_{50}$[a] | E(exposure) greater than observed effects[b] | E(exposure) less than observed effects[b] | No exposure[c] |
|---|---|---|---|---|---|
| Scenarios | 8 | 2 | 18 | 52 | 10 |
| % of total | 8.9 | 2.2 | 20.0 | 57.8 | 11.1 |
| | | Average exposure | | | |
| Unprotected, (mg-min/m$^3$) | 3,930 | 300 | 60 | .9 | 0 |
| Protected, (mg-min/m$^3$) | 1,700 | 50 | 10 | .2 | 0 |
| | | Average exposure reduction | | | |
| Overall, % | 66.8 | 82.7 | 67.8 | 64.6 | 0.0 |
| Relative, % | 87.6 | 98.2 | 83.5 | 81.3 | 0.0 |
| | | Respiratory device | | | |
| NATO[d], % | 8.9 | 2.2 | 20.0 | 57.8 | 11.1 |
| US[d], % | 8.9 | 2.2 | 20.0 | 57.8 | 11.1 |
| | | Meteorological conditions | | | |
| WS 1 m/s, % | 20.0 | 6.7 | 33.3 | 6.7 | 33.3 |
| WS 3 m/s, % | 6.7 | 0.0 | 20.0 | 73.3 | 0.0 |
| WS 6 m/s, % | 0.0 | 0.0 | 6.7 | 93.3 | 0.0 |
| | | Downwind distance | | | |
| 3 km, % | 20.0 | 6.7 | 33.3 | 40.0 | 0.0 |
| 10 km, % | 6.7 | 0.0 | 26.7 | 66.7 | 0.0 |
| 20 km, % | 0.0 | 0.0 | 0.0 | 66.7 | 33.3 |

[a]Expected exposure exceeds $LCt_{50}$ for males and infants assuming light activity (see Tables 3.2 and 3.3).

[b]Expected exposure exceeds (greater than) or does not attain (less than) observed effects threshold for adults (see Tables 3.2 and 3.3).

[c]"No exposure" indicates that plume did not arrive in the first 3 h under the given condition.

[d]Assuming continuous leak rate of 15%, NATO (civilian) filter canister breakthrough standard of 3000 mg-min/m$^3$, and U.S. military-issue M17 filter canister breakthrough standard of 159,000 mg-min/m$^3$.

that are likely to be observable about 22% of the time, while GB Class I scenarios were in this category about half that often; expected exposures below those that are likely to result in observable effects are anticipated in 27% of the Class I releases and decrease with accident class to around 11% of the Class V accidents. Because of the relationship between time and distance, the 1-m/s winds fail to reach a 20-km downwind distance in 180 min.

The average overall GB exposure reduction obtained when using respiratory protection is 64.6% when compared with unprotected exposure. Across all exposure categories, use of selected respiratory devices reduced average overall exposure by 64% to 83%. The calculated effectiveness of the two filter designs does not appreciably vary across scenarios because the estimated Ct's exceed the sorptive capacity of the filter canister only when an H/HD Class V accident at 3-km distance, with 1 m/s winds, and with a NATO-standard filter canister, was considered. Exposure is largely driven by the proportion of masks that leak, which is held constant at 15%. This finding suggests that either filter design would be equally effective for the GB release scenarios considered and that effort should be focused on reducing the estimated leak rate.

Under rapid-onset wind speeds (6 m/s), an overwhelming majority of the GB release scenarios examined (93.3%) are expected to result in exposures for which no effects will be observed. The remaining 6.7% are expected to generate exposures exceeding the threshold for observable effects. None of the exposures in this latter category approach the incapacitating level [i.e., $ICt_{50}$ of 35 to 72 mg-min/m$^3$ (U.S. Department of the Army 1988)]. At these high windspeeds, the plume moves and disperses too quickly to generate lethal exposures.

At moderate wind speeds of 3 m/s, a smaller majority of scenarios (73.3%) are expected to result in exposures below the threshold for observable effects; 20% exceed the observable effect threshold. Of those exceeding the threshold, 6.7% are expected to generate exposures greater than the $LCt_{50}$ for males.

At low wind speeds of 1 m/s, 33.3% of the scenarios generate plumes that result in no exposure at 20 km from the source. Another 33.3% are expected to result in concentrations that meet or exceed the observable effects threshold; some of the protected exposures in this category approach or are contained within the range for adult incapacitation [i.e., $ICt_{50}$ of 35-72 mg-min/m$^3$, (U.S. Department of the Army 1988)]. Approximately a fourth (26.7%) are projected to generate concentrations greater than either the infant or adult male $LCt_{50}$ values primarily at distances of 3 km or less from the source. The remaining 6.7% of the scenarios result in exposures below the $ECt_{50}$.

All GB scenarios examined for 20 km (a distance dilution effect) resulted in expected exposures below the threshold effect level, indicating that special respiratory protection would not be critical at such distances from the source. At 10 km, fatalities would occur in some (6.7%) of the scenarios, but more (26.7%) would occur at 3 km. In addition, some of the scenarios resulting in exposures exceeding the observable effects threshold at 3 km are expected to result in incapacitating effects. Only 40% of the scenarios examined for 3 km would result in exposures less than the observable effects threshold, while a significant number of potential scenarios would generate fatalities (26.7%) or responses ranging from minor tremors to convulsions and severe respiratory distress (33.3%).

For this appraisal, "protected" exposures of this magnitude are primarily the result of 15% of the devices employed leaking around the filter and not filter breakthrough. Strong consideration should be given to measures for substantially reducing the ability of the public to avoid leakage when self-donning respiratory devices by whatever means (thorough fit testing, accommodation for corrective lens wearers, use of respirators in conjunction with hoods, and training, etc.).

### 7.2.2 Nerve Agent VX Scenarios

A descriptive summary of the screening analysis results for respirator use under the selected VX scenarios is presented in Table 7.5. Of the 90 VX scenarios, 17.7% (n = 16) resulted in expected exposures that exceed the estimated $LCt_{50}$ for either adult males or infants (see Table 3.3). Half of the high-exposure release scenarios are the result of a VX Class V release, one-third result from VX Class IV accidents, and the rest result from VX Class III releases. These high-exposure releases result in exposures exceeding the $LCt_{50}$ for adult males. All of the respiratory response scenarios resulting in expected exposures greater than the $LCt_{50}$ for newborn infants but not exceeding the $LCt_{50}$ for adult males (four in all) are equally split between GB class II and III accidents. Scenarios resulting in expected exposures below the $LCt_{50}$ for infants are distributed among all accident classes; Class I, II, and III accidents are in this category of exposure about 17% of the time, while Class IV and V scenarios are in this category about 22 and 28% of the time, respectively. Expected exposures below those that are likely to generate observable effects are anticipated in 36% of the Class I releases and decrease with accident class to around 14% of the Class IV accidents and none of the Class V accidents. Because of the relationship between time and distance, the 1-m/s winds fail to reach a 20 km downwind distance in the first 3 h.

The average overall VX exposure reduction obtained when using respiratory protection is 69.4% when compared with the exposures estimated for the unprotected population. Across all exposure categories, use of selected respiratory devices reduces average overall exposure by 59 to 84%. The calculated effectiveness of the two filter designs does not appreciably vary across scenarios because the estimated Ct's rarely exceed the sorptive capacity of the filter canister. The cases in which protected exposures exceed the $LCt_{50}$ for newborn infants or adult males are largely the result of leakage rather than filter failure and resulting breakthrough and occurred under conditions of large releases (at 3- and 10-km distances with 1 m/s winds). These findings suggest that either filter design would be equally effective for the VX release scenarios considered and that effort should be focused on reducing the estimated leak rate.

Under rapid-onset wind speeds (6 m/s), a majority (60.0%) of the VX release scenarios examined are expected to result in exposures for which no effects will be observed. The remaining 40.0% are estimated to result in exposures that exceed the threshold for observed effects, but none will approach the VX threshold for adult incapacitation [i.e., $ICt_{50}$ of 24 mg-min/m$^3$, (U.S. Department of the Army 1988)]. None of the VX release scenarios at 6 m/s is expected to result in exposures that approach the adult or infant $LCt_{50}$.

Table 7.5. Descriptive summary of screening analysis results for scenarios involving VX and respiratory protection

| | E(exposure) greater than $LCt_{50}$ for adult males[a] | E(exposure) greater than infant $LCt_{50}$[a] | E(exposure) greater than observed effects[b] | E(exposure) less than observed effects[b] | No exposure[c] |
|---|---|---|---|---|---|
| Scenarios | 12 | 4 | 36 | 28 | 10 |
| % of total | 13.3 | 4.4 | 40.0 | 31.1 | 11.1 |
| | | **Average exposure** | | | |
| Unprotected, (mg-min/m$^3$) | 7,580 | 140 | 10 | .1 | 0 |
| Protected, (mg-min/m$^3$) | 4,090 | 20 | 3 | .02 | 0 |
| | | **Average exposure reduction** | | | |
| Overall, % | 71.6 | 83.9 | 59.5 | 69.4 | 0.0 |
| Relative, % | 95.5 | 99.1 | 76.3 | 86.4 | 0.0 |
| | | **Respiratory device** | | | |
| NATO[d], % | 13.3 | 4.4 | 40.0 | 31.1 | 11.1 |
| US[d], % | 13.3 | 4.4 | 40.0 | 31.1 | 11.1 |
| | | **Meteorological conditions** | | | |
| WS 1 m/s, % | 33.3 | 13.3 | 20.0 | 0.0 | 33.3 |
| WS 3 m/s, % | 6.7 | 0.0 | 60.0 | 33.3 | 0.0 |
| WS 6 m/s, % | 0.0 | 0.0 | 40.0 | 60.0 | 0.0 |
| | | **Downwind distance** | | | |
| 3 km, % | 26.7 | 6.7 | 60.0 | 6.7 | 0.0 |
| 10 km, % | 13.3 | 6.7 | 40.0 | 40.0 | 0.0 |
| 20 km, % | 0.0 | 0.0 | 20.0 | 46.7 | 33.3 |

[a]Expected exposure exceeds $LCt_{50}$ for males and infants assuming light activity (see Tables 3.2 and 3.3).

[b]Expected exposure exceeds (greater than) or does not attain (less than) observed effects threshold for adults (see Tables 3.2 and 3.3).

[c]"No exposure" indicates that plume did not arrive in the first 3 h under the given condition.

[d]Assuming continuous leak rate of 15%, NATO (civilian) filter canister breakthrough standard of 3000 mg-min/m$^3$, and U.S. military-issue M17 filter canister breakthrough standard of 159,000 mg-min/m$^3$.

At moderate wind speeds of 3 m/s, only 33.3% of the scenarios are expected to result in exposures that are below the threshold for observable effects. Of the remaining 66.7%, 60% are not expected to exceed the threshold for adult incapacitation. The remainder (6.7%) are expected to generate exposures greater than the $LCt_{50}$ for males.

At low wind speeds of 1 m/s, a third of the scenarios generate plumes that result in no exposure, primarily at extended (20-km) distances from the source. Twenty percent of the remaining scenarios result in concentrations that meet or exceed the observable effects threshold; many of these are estimated to generate concentrations that approach or exceed the threshold for adult incapacitation [i.e., $ICt_{50}$ of 24 mg-min/$m^3$, (U.S. Department of the Army 1988)]. The remainder (46.6%) are expected to result in concentrations greater than either the infant or adult $LCt_{50}$.

All VX scenarios examined for distances equal to 20 km resulted in no expected fatal exposure levels 3 h after agent release. In one third of the cases, the plume did not arrive at this distance within the first 3 h following release, and nearly half (46.7%) resulted in estimated exposures less than the observed effect threshold. Some (20%) could be expected to result in observable effects. These data indicate that use of respirators at this distance would not be critical but could reduce the size of the population exhibiting threshold effects. At 10 km, fatalities are expected to occur in 20% of the scenarios examined, and several of those falling in the exceed-observable-effects category would generate incapacitating exposures. At 3 km, more scenarios would generate fatalities (33.4%) or incapacitating exposures. Only 6.7% would result in no observable effects.

VX possesses low volatility [10.5 mg/$m^3$ at 25°C (U.S. Department of the Army 1974)] and is not likely to be transported for long distances as a vapor. VX aerosols are readily transported but will be removed efficiently by a respirator having either NATO civilian or U.S. military-issue standard filter capacity. The respiratory protection analysis indicates that populations within 3 km of a major VX release are likely to receive fatal exposures and that respiratory protection can provide an important degree of exposure reduction at this distance from the source. Under the assumption that 15% of the devices implemented leak, fatal or incapacitating exposure can occur fairly quickly at low wind speeds (plume accumulates). Strong consideration should be given to measures for substantially reducing the leak rate by whatever means (thorough fit testing, accommodation for corrective lens wearers, use of respirators in conjunction with hoods, etc.).

### 7.2.3 Blister Agent Mustard (H/HD) Scenarios

A descriptive summary of the screening analysis results for respirator use under the selected H/HD release scenarios is presented in Table 7.6. Of the 72 H/HD scenarios, 20.9% (n = 15) resulted in expected exposures that exceed the estimated $LCt_{50}$ for either adult males or infants (see Table 3.3). Roughly 60% of the high-exposure release scenarios are the result of an H/HD Class V release, with about 4% resulting from H/HD Class IV accidents. These high-exposure releases result in exposures exceeding the $LCt_{50}$ for adult males. The respiratory response scenarios resulting in expected exposures greater

Table 7.6. Descriptive summary of screening analysis results for scenarios involving H/HD and respiratory protection

| | E(exposure) greater than $LCt_{50}$ for adult males[a] | E(exposure) greater than infant $LCt_{50}$[a] | E(exposure) greater than observed effects[b] | E(exposure) less than observed effects[b] | No exposure[c] |
|---|---|---|---|---|---|
| Scenarios | 12 | 3 | 49 | NA | 8 |
| % of total | 16.7 | 4.2 | 68.1 | NA | 11.1 |
| | | Average exposure | | | |
| Unprotected, (mg-min/$m^3$) | 283,000 | 2,250 | 270 | NA | 0 |
| Protected, (mg-min/$m^3$) | 243,000 | 1,120 | 50 | NA | 0 |
| | | Average exposure reduction | | | |
| Overall, % | 41.8 | 53.6 | 70.3 | NA | 0.0 |
| Relative, % | 87.4 | 77.8 | 85.7 | NA | 0.0 |
| | | Respiratory device | | | |
| NATO[d], % | 19.4 | 5.6 | 63.9 | NA | 11.1 |
| US[d], % | 13.9 | 2.8 | 72.2 | NA | 11.1 |
| | | Meteorological conditions | | | |
| WS 1 m/s, % | 33.3 | 4.2 | 29.2 | NA | 33.3 |
| WS 3 m/s, % | 16.7 | 4.2 | 79.2 | NA | 0.0 |
| WS 6 m/s, % | 0.0 | 4.2 | 95.8 | NA | 0.0 |
| | | Downwind distance | | | |
| 3 km, % | 29.2 | 12.5 | 58.3 | NA | 0.0 |
| 10 km, % | 20.8 | 0.0 | 79.2 | NA | 0.0 |
| 20 km, % | 0.0 | 0.0 | 66.7 | NA | 33.3 |

[a]Expected exposure exceeds $LCt_{50}$ for males and infants assuming light activity (see Tables 3.2 and 3.3).

[b]Because mustard is considered a carcinogen there is no observable effects threshold (see Tables 3.2 and 3.3).

[c]"No exposure" indicates that plume did not arrive in the first 3 h under the given condition.

[d]Assuming continuous leak rate of 15%, NATO (civilian) filter canister breakthrough standard of 1000 mg-min/$m^3$, and U.S .military-issue M17 filter canister breakthrough standard of 159,000 mg-min/$m^3$.

than the $LCt_{50}$ for newborn infants but not exceeding the $LCt_{50}$ for adult males (three in all) are equally split between H/HD Class III, IV, and V accidents. Scenarios resulting in expected exposures below the $LCt_{50}$ for infants are distributed among all accident classes, with Class II and III accidents accounting for about one in three scenarios and Classes V and IV accounting for about one in five or six scenarios respectively. The 1-m/s winds fail to reach a 20-km downwind distance in the first 3 h; hence, for each accident class considered, a fifth of the scenarios result in no exposure. Because mustard is considered a carcinogen, it is not appropriate to consider exposure scenarios as resulting in less than observable effects.

The majority (68.1%) of mustard scenarios generate concentrations that exceed the observable acute effect threshold but do not attain an $LCt_{50}$ level. The average overall expected H/HD exposure reduction obtained when using respiratory protection is greater than 40% in all exposure categories (adult male) when compared with unprotected exposure. Across all exposure categories, use of the selected respiratory devices reduces average overall exposure by 41 to 70%. The differences in estimated effectiveness of the two filter designs varies from 2.8 to 8.3%, depending on the category of exposure. The U.S. military-issue standard design provides the greatest protection in each exposure category.

Breakthrough occurred in nine of the accident scenarios considered; all involve the use of NATO civilian standard filters and include five SL 28, three SL 5, and one SL 4 incidents (see Table 4.2). No breakthrough was estimated when respirator filter design met U.S. military-issue standards. However, note that under large release and long-duration conditions, the current operating assumption, that 15% of the devices used will leak, generated fatal exposure estimates for the protected population.

Under rapid onset wind speeds (6 m/s), all scenarios generated exposures in excess of the observable acute effects threshold, but only 4.2% would achieve exposures greater than the infant $LCt_{50}$ exposure. No mustard exposure generated at this wind speed achieved the adult $LCt_{50}$ level.

At the moderate wind speed of 3 m/s, all scenarios examined generated exposures in excess of the observable acute effects threshold. A total of 20.9% are expected to generate exposures in excess of $LCt_{50}$ values for adults/infants, and the remainder (79.2%) would generate exposures in excess of the observable acute effects threshold (skin irritation, blistering, and chemical burns). One of these scenarios (SL 5) representing H/HD Class III is expected to generate protected exposures approaching adult incapacitation levels [i.e., $ICt_{50}$ of 1000 to 2000 mg-min/m$^3$ for masked individuals (U.S. Department of the Army 1988)]. Several scenarios in the observed acute effects category would generate exposures that exceed the incapacitating level for eye damage (i.e., $ICt_{50}$ of 200 mg-min/m$^3$; App. B, U.S. Department of the Army 1988).

At low wind speeds of 1 m/s, one-third of the scenarios would generate plumes that would move too slowly to result in exposures within the first 3 h after the time of release. An additional 29.2% of the 1 m/s scenarios examined result in observable effects levels. All remaining 1 m/s scenarios are expected to generate exposures in excess of the infant or adult $LCt_{50}$. Most of the 3 and 6 m/s scenarios result in expected exposures below the $LCt_{50}$ for infants, with 79.2 and 95.8% respectively. The remaining 6 m/s scenarios and

4.2% of the 3 m/s scenarios result in exposures above the $LCt_{50}$ for infants, and 16.7% of the 3 m/s scenarios result in exposures greater than the $LCt_{50}$ for adult males.

When mustard scenarios were examined for distance, it became clear that fatalities and serious burns (41.7%) would occur within 3 km of the source even with respiratory protection. All scenarios would generate at least observable effects at this distance, as well as at 10 km; however, fewer serious injuries and/or fatalities (i.e., 20.8%) would occur at the greater distance. One-third (33.3%) of the scenarios generate no exposure at 20 km from the source in the first 3 h; the remainder would result in exposures that exceed the observable effects threshold. In an H/HD Class V scenario, unprotected individuals at 20 km could receive exposures (on the order of 800 mg-min/$m^3$) well above that at which vision effects are incapacitating (i.e., 200 mg-min/$m^3$) and would experience burns to the skin and respiratory passages. No scenarios examined are expected to result in exposures at the $LCt_{50}$ level at 20 km.

The high percentage of fatal mustard scenarios presented in this analysis (Table 7.6) is largely the result of cumulative exposure in slow-moving plumes generated by large-scale incidents. Note that simplifying assumptions of vapor generation were incorporated into this analysis. Mustard possesses reasonably low volatility [925 mg/$m^3$ at 25 C (U.S. Department of the Army 1974)] and is not likely to be transported for long distances as a vapor. Mustard aerosols are transported readily but will be removed efficiently by a respirator having either NATO civilian or U.S. military-issue standard filter capacity. The respiratory protection analysis indicates that unprotected populations within 10 km of a major mustard release are likely to receive fatal exposures and that respiratory protection can provide an important degree of exposure reduction.

Table 7.7 summarizes the nature of scenarios that lead to breakthrough of filter capacity. Only 16 of 252 scenarios examined lead to breakthrough, which tends to confirm that greater emphasis should be placed on the reduction and minimization of leakage around respiratory devices. Furthermore, these breakthroughs occur most frequently with NATO standard devices. Very frequently they occur at close proximity to the release under very low wind speeds and stable meteorological conditions.

## 7.3 ANALYSIS OF SELECTED SCENARIOS

Using the scenarios and analyses discussed in Sect. 7.2, a preliminary analysis of the effectiveness of respiratory protection under various conditions can be made. This analysis is based on the implementation of an indoor-outdoor warning system, a decision support system with a rapid response time, and public education and training in the use of respiratory protection.

Figure 7.2 examines the effectiveness of NATO and U.S. military respiratory devices, characterized by a 15% leak rate and exposures below breakthrough values. Comparison of the expected exposure with the capacity of the respiratory device, given the leakage, shows clearly that respiratory devices are only as good as the emergency response system that elicits a response from the people to be protected. In this case, even though the capacity of the device itself would reduce exposures below the $LCt_{50}$ for newborn infants,

Table 7.7. Summary of scenarios leading to breakthrough

| Accident class | 3-h exposure[a] (mg-min/m$^3$) | Breakthrough standard | | Downwind distance | | Wind speed | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | NATO | U.S. | 3 km | 10 km | 1 m/s | 3 m/s | 6 m/s | |
| GB V | 12,620 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| VX IV | 1,810 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| VX V | 35,990 | 2 | 0 | 1 | 1 | 2 | 0 | 0 | 2 |
| H/HD III | 1,887 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| H/HD IV | 574,600 | 3 | 1 | 3 | 1 | 3 | 2 | 0 | 4 |
| H/HD V | 921,000 | 5 | 2 | 4 | 3 | 4 | 1 | 1 | 7 |
| Total | | 13 | 3 | 11 | 5 | 12 | 3 | 1 | 16 |

[a]Expected cumulative exposure in protected environments for worst accident in class.

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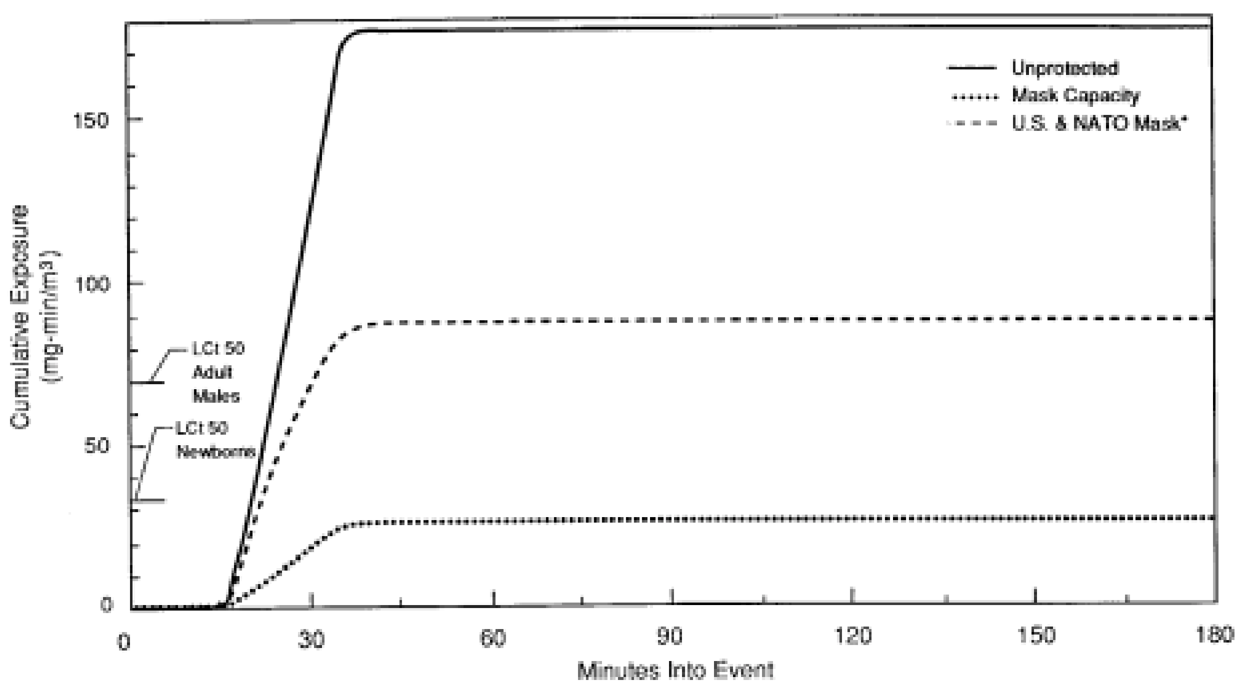


**Fig. 7.2. Respiratory protection scenarios at 3-km distance for GB class V events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. *Because no breakthrough occurs, and because a 15% leak rate is used for each, both NATO and U.S. masks are represented by the same expected exposure curve.

many people would be exposed before getting the device in operation due to the time necessary to decide to warn, receive warning, decide to respond, and implement the protection.

Figure 7.3 presents respiratory protection scenarios for a large VX Class IV event at a 3-km downwind distance and a slower onset of 1-m/s winds. In this instance, emergency response is adequate to ensure the use of respiratory protection by most people before the onset of the plume, which is indicated by the similarity of the curves for the expected exposure and the capacity of the devices. Unfortunately, in this instance, the slower onset is accompanied by a higher concentration of agent arriving at 3-km downwind distance. Hence, the sheer size of the release overwhelms the protection offered by a device with a 15% leak rate. In this case, even a leakage rate that is three times smaller (5%) leads to an exposure that is about three times the $LCt_{50}$ for adult males at the end of the first 3 h. This occurs because of the large concentrations present in the unprotected environment for about an hour as the plume passes. This seems to indicate that even fairly modest leak rates will not provide acceptable protection from large releases where concentrations remain high over fairly long periods. Hence, efforts in conjunction with respiratory protection in such cases must reduce either the concentrations of agent at each time interval or the overall time spent in the toxic environments (e.g., via in-place sheltering or evacuation, respectively).

For relatively small releases of agent, respiratory protection may be used to minimize the observable effects. For example, Fig. 7.4 presents the NATO and U.S. military standard respiratory devices for a GB Class II event under 3-m/s winds. In this scenario, the device can be used to reduce the overall level of exposure, and most people could tolerate the resulting miosis and tremors. But because of the carcinogenic property of mustard agent, it would be remiss to recommend such protective action in conjunction with mustard releases.

## 7.4 RESPIRATORY PROTECTION CONCLUSIONS

Breakthrough of the filter canister was determined to be a problem mostly for mustard scenarios that included use of NATO civilian-standard filters. In all other agent scenarios, fatal exposures for protected populations were the result of exposure via leaky respirator seals and the timing of warning, response, and implementation. The constant 15% leakage rate assumed in the analysis may be greater than what is likely during actual implementation among a public with heterogeneous facial configurations, facial hair patterns, and eyewear use. However, this analysis clearly points out the need for careful fitting, seal maintenance, and consideration of supplemental protection to reduce infiltration (such as the use of hoods in combination with a respirator). Moreover, this analysis suggests that even relatively small leakage rates can accumulate exposure when the concentrations are high or the plume is long. Hence, any mitigation of the respirator seal problem will significantly reduce the potential for fatalities with this protective action. Respirators made available for civilian use should incorporate filter design specifications at least as stringent as the U.S. military-issue standard (i.e., Ct = 159,000 mg-min/$m^3$).

Respiratory protection is effective within 10 km and most effective within 3 km. At 20 km, respiratory protection is unlikely to be required for the public. Respiratory

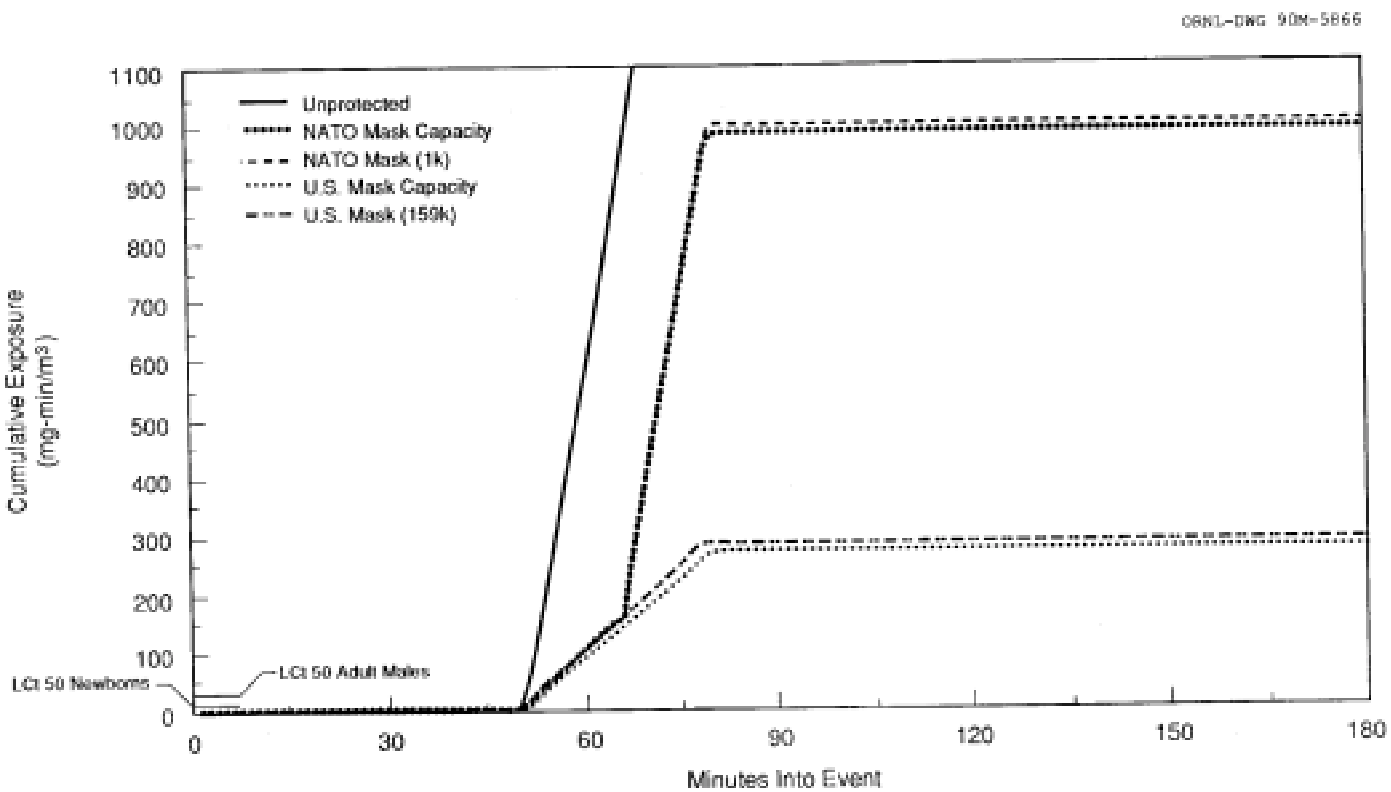


**Fig. 7.3. Respiratory protection scenarios at 3-km distance for VX class IV events when 1-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population.

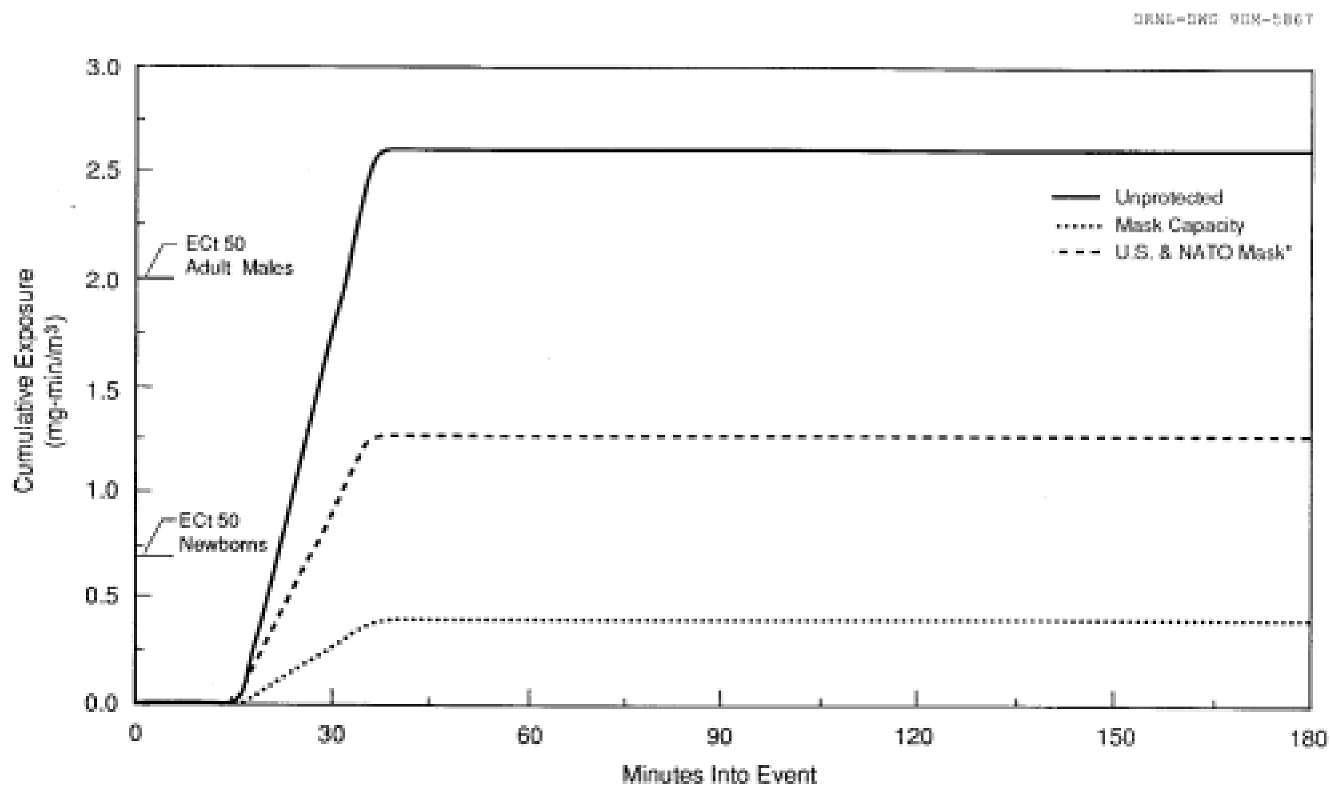


**Fig. 7.4. Respiratory protection scenarios at 3-km distance for GB class II events when 3-m/s winds prevail.** Note that $ECt_{50}$ equals concentration-time integral where 50% of reference population are expected to exhibit observable effects. Because no breakthrough occurs, and a 15% leak rate is used for each, both NATO and U.S. masks are represented by the same curve.

protection for individuals at 3 and 10 km lends itself well to combined approaches, where sheltering or various types or evacuation can be performed in combination with respirator use (see Sect. 8.2).

The maintenance and fitting requirements necessary for effective respirator use would be best served by institutional management and device ownership at the local level. Community health departments could handle the responsibility of training and fitting the protected population, distributing respiratory devices, and running periodic maintenance checks and drills.

# 8. COMPARISON OF ALTERNATIVES

This section compares various alternatives to protect the public in the event of a chemical agent emergency. First, the competing alternatives of evacuation and in-place sheltering are examined. Second, the complementary alternatives of respiratory protection with either evacuation or in-place sheltering are examined. The comparison of alternatives, analysis of the degree of protection afforded, and the preliminary recommendations presented in this report are subject to a number of qualifications that limit the nature of the research and thereby the resulting conclusions.

- The results of this analysis assume that a very sophisticated emergency response capability exists. This includes the capability of detecting a release, assessing its severity, and making a decision to warn the public in less than 5 min; a sophisticated indoor/outdoor warning system, including effective warning messages that make the hazard salient and elicit appropriate emergency responses; and adequate public information and education programs to ensure a timely decision by the people at risk to respond to the emergency.
- The assumptions about human behavior are sometimes based on limited empirical evidence and are thereby subject to uncertainty.
- No attempt to test failure rates of various types of equipment was undertaken in this research; hence, the assumptions about technology also have associated uncertainty.
- The estimation of the expected exposures via the plume dispersion model involves substantial uncertainty, probably on the order of ±50%.
- Only a limited number of scenarios (504 evacuation, 378 in-place protection, and 252 respiratory protection) of the unlimited potential scenarios have been examined.

## 8.1 COMPETING ALTERNATIVES: EVACUATION VS IN-PLACE SHELTER

This section compares the advantages and disadvantages of mutually exclusive protective action alternatives. Specifically, it compares avoiding exposure via evacuation and protecting people from exposure via in-place protection. There are two types of comparisons required, the comparison of evacuation with in-place protection measures that (1) reduce but do not eliminate exposure entirely in the protected environment and (2) eliminate exposure completely in the protected environment.

### 8.1.1 Evacuation vs Reduced Infiltration

Intuitively, when evacuation is completed, exposure is avoided, as long as the destination is not impacted by the plume. Whenever it can be completed before the plume arrives, evacuation is inherently superior to in-place protection alternatives that reduce, but do not eliminate, exposure. Because the likelihood of completing an evacuation within 50 min of a release is high (i.e., there is about a 75% chance that a 20-min clearance time evacuation will be completed, more than 90% chance that a 10-min

clearance scenarios will be completed, and more than a 95% chance that 5- and 1-min clearance scenarios will be completed), evacuation will be superior for releases involving significant concentrations of agent when a minimum 50-min onset time is available. Specifically, evacuation is likely to be superior in response to large releases for areas 10 km or farther from the source point, and even for areas closer when winds speeds are slower (e.g., arrival is around 50 min at 3 km under 1-m/s winds).

Moreover, because the likelihood of completing enhanced sheltering is greater than 95% for release scenarios arriving in 50 min or more, the driving force in the comparison is the exposure in the protected environment. The likelihood of completing expedient protective action measures is approximately 75% for release scenarios arriving in 50 min or more; thus, the extent of exposure reduction is also an important factor in the comparison between evacuation and expedient measures of in-place protection. Because exposures within reduced infiltration in-place shelters continue to increase as fresh air infiltrates the protected environment, and because this can generate larger expected exposures than the unprotected environment originally presented (Cf. Appendix I), evacuation is preferable to reduced infiltration alternatives.

Figures 8.1 and 8.2 present a comparison between evacuation scenarios characterized by 5- and 10-min clearance times and enhanced and expedient sheltering for Class III GB and VX accidents, respectively, with 3- and 1-m/s winds at 3 km downwind. Evacuation is the preferred alternative under the slower onset accident scenario of Fig. 8.2, but even in the more rapid onset associated with the scenario in Fig. 8.1, evacuation would be preferred to the limited protection offered by expedient shelters and the limited duration of protection offered by enhanced shelters. Moreover, the potential for exposure reduction for evacuation scenarios is greater than the capacity to reduce exposure in the reduced infiltration shelters (i.e., evacuation, even with a clearance time of 10 min potentially eliminates all exposure, while reduced infiltration sheltering alternatives do not). Finally, evacuation offers complete protection in one step, as opposed to the second step of vacating the reduced infiltration shelters at an appropriate time.

Even in Class II events, characterized by the relatively slow onset of 1-m/s winds, such as the one examined in Fig. 8.3, evacuation would be likely to be preferred over reduced infiltration in-place alternatives because it reduces the exposure more and it can completely eliminate the exposure for those people completing the evacuation before the plume's impact. Hence, when considering lethal concentrations of agent, evacuation responses are likely to be preferred over the reduced infiltration alternatives considered herein.

However, for relatively small releases of either VX or GB, where the concern is overprotection from observed effects (i.e. miosis and tremors), the preference may shift to in-place options. For example, Fig. 8.4 considers a GB Class II event at 3 km under 3-m/s winds. In this instance, the distinction between the reduced infiltration alternatives and the evacuation options is negligible at best. These alternatives are indistinguishable for this release scenario. In this case, emergency managers will be forced to rely on other factors and judgments to make the recommendation for one option over another. For example, if such a release occurs in hours of darkness, the increased risks associated with driving with miosis (of the eyes) may outweigh the additional protection afforded by a 10-min clearance over a 0.2 ACH in-place shelter. Furthermore, emergency decision

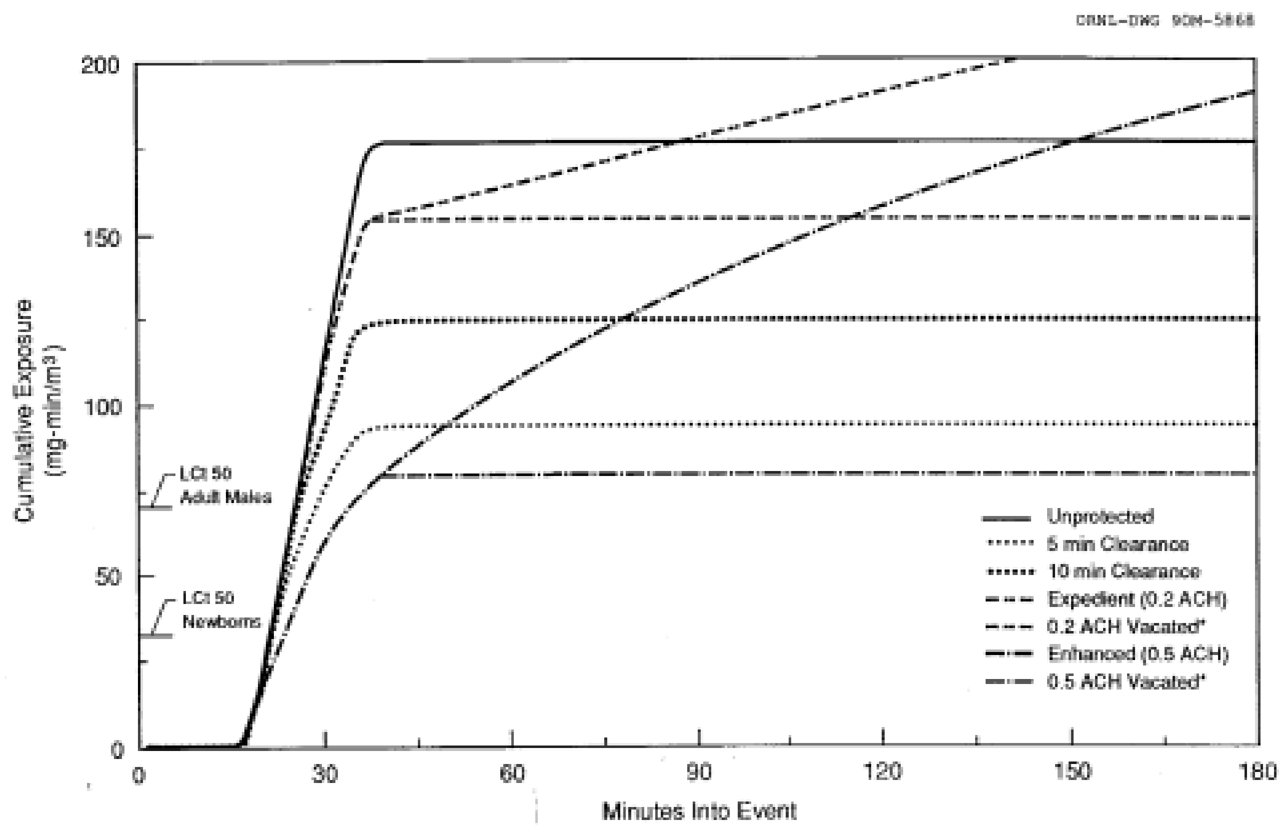


**Fig. 8.1. Comparison of evacuation and in-place scenarios at 3-km distance for GB class V events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr. *Exposure curve is flat after the plume passes because the shelter is vacated when the concentration outside is less than that inside.

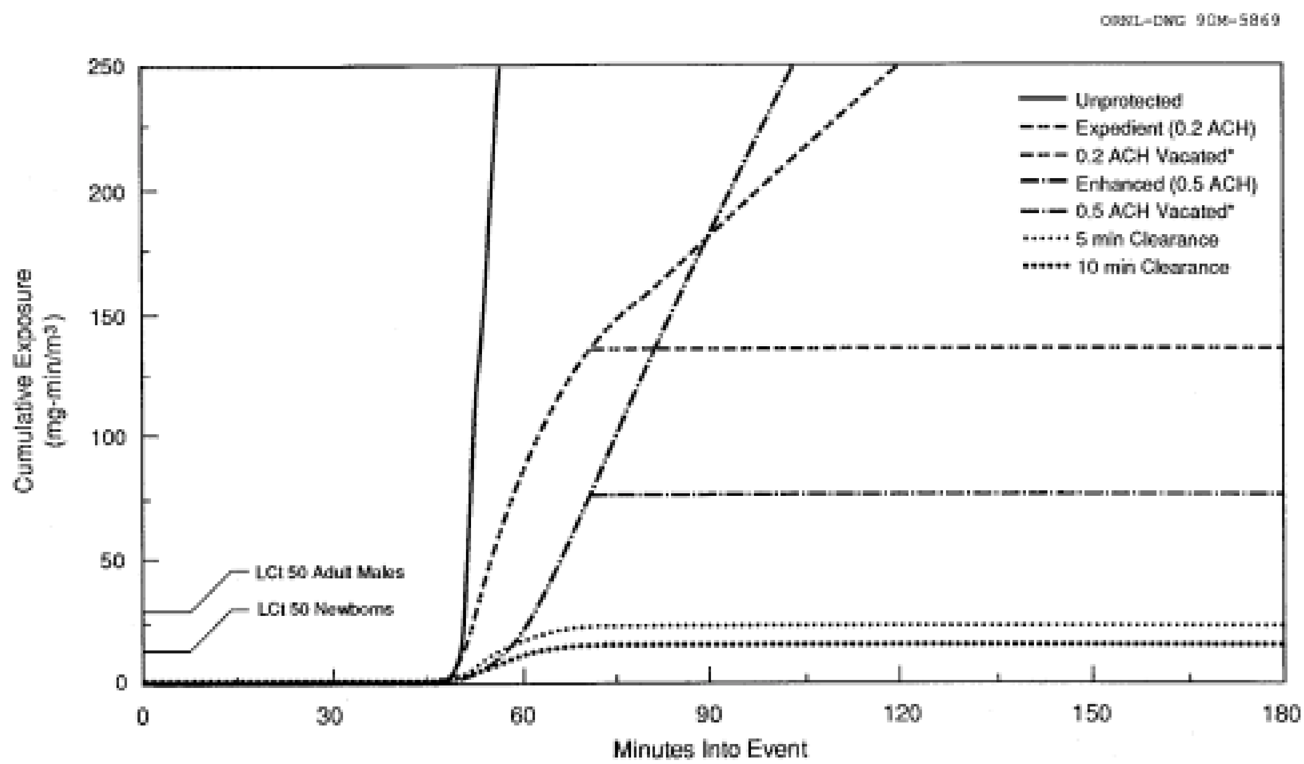


**Fig. 8.2. Comparison of evacuation and in-place scenarios at 3-km distance for VX class III events when 1-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr. *Exposure curve is flat after the plume passes because the shelter is vacated when the concentration outside is less than that inside.

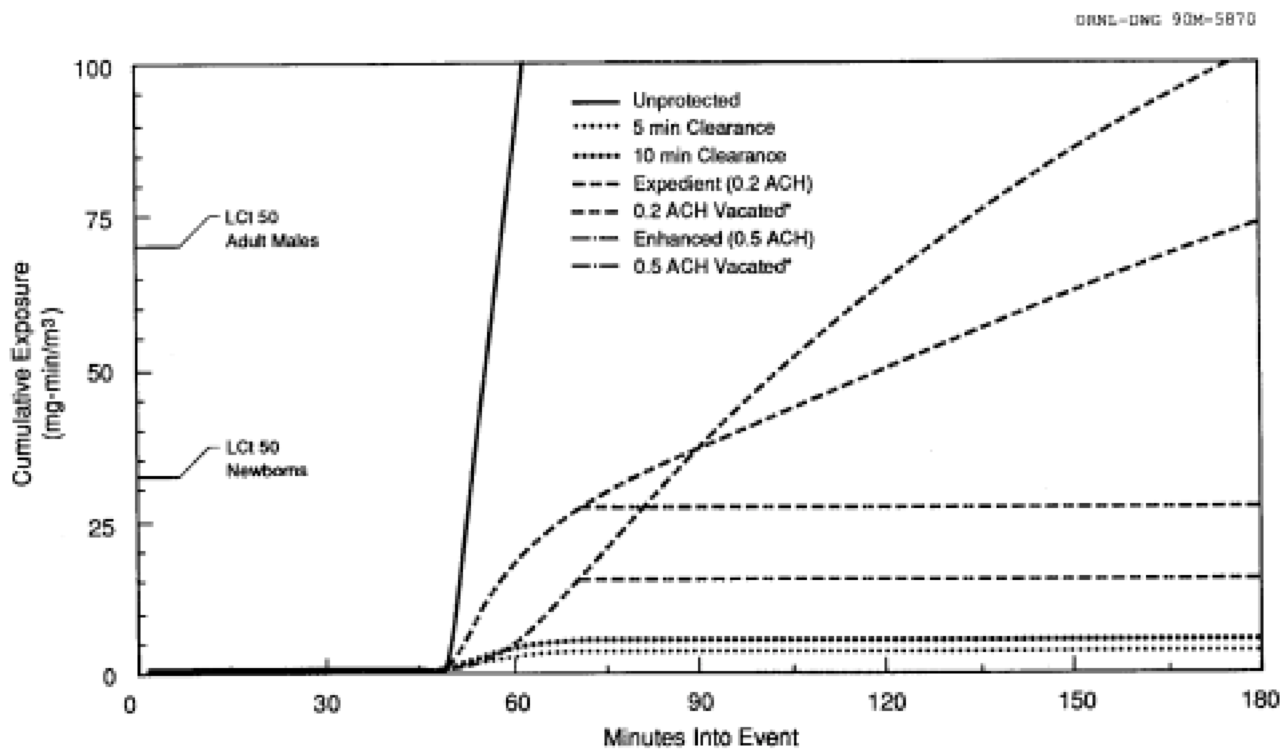


Fig. 8.3. Comparison of evacuation and in-place scenarios at 3-km distance for GB class II events when 1-m/s winds prevail. Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr. *Exposure curve is flat after the plume passes because the shelter is vacated when the concentration outside is less than that inside.

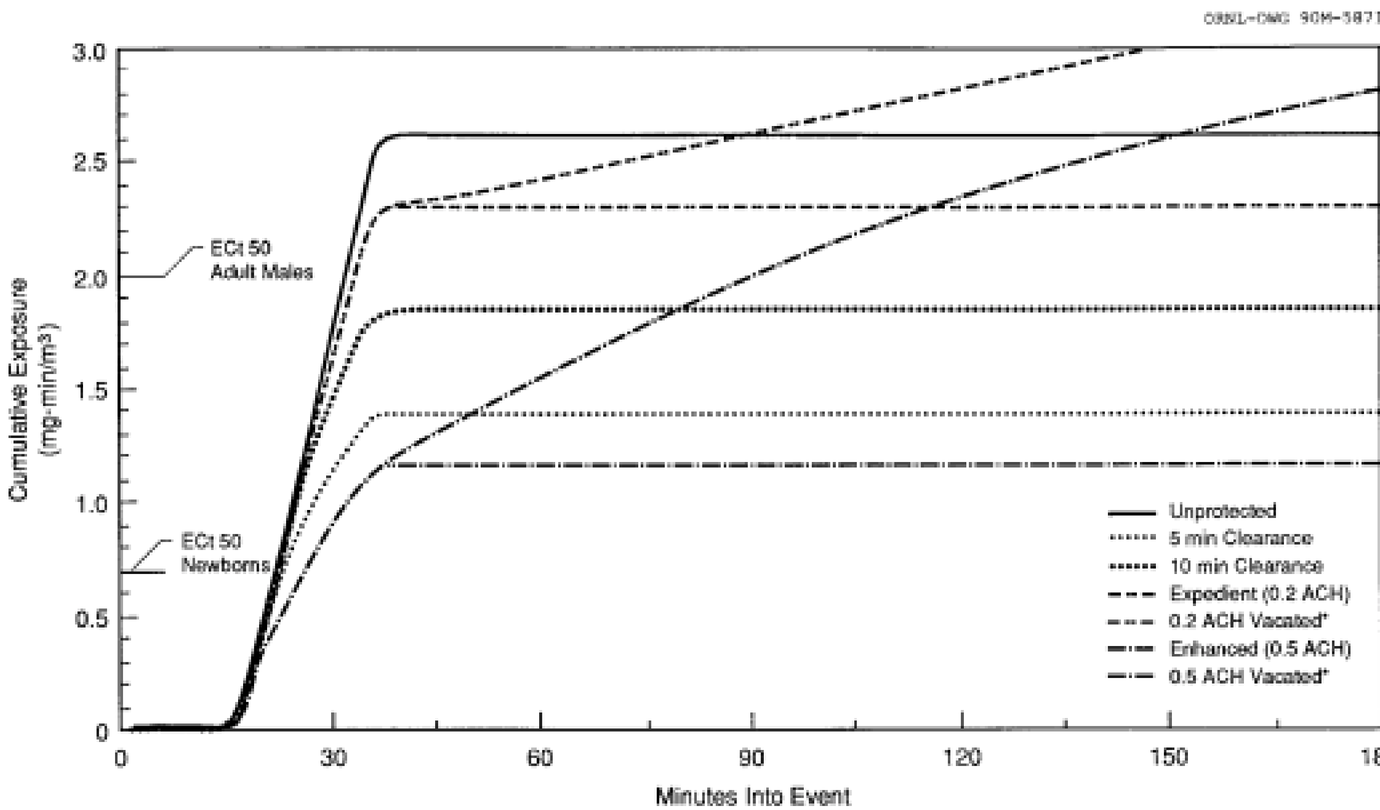


**Fig. 8.4. Comparison of evacuation and in-place scenarios at 3-km distance for GB class II events when 3-m/s winds prevail.** Note that $ECt_{50}$ equals concentration-time integral, where 50% of reference population are expected to exhibit observable effects. ACH equals air changes/hr. *Exposure curve is flat after the plume passes because the shelter is vacated when the concentration outside is less than that inside.

makers may want to consider the degree of protection already afforded some populations. For example, if the release characterized in Fig. 8.4 were to occur in winter months, during hours when most people would likely be home indoors, having people remain indoors may be quite useful. Emergency managers could even augment each structure's ability to limit infiltration passively, by having electrical power turned off in the area(s) likely to be impacted. This would automatically shut down whole-house circulating systems and reduce the amount of infiltration; one consequence of this action, however, would be that warning via electrical devices (e.g., radios and televisions) would be eliminated another consequence is the loss of traffic signal operations for potential evacuation routes. Before shutting off electric power in areas, emergency managers will also need to be sure that hospitals have operable automatic backup power systems to avoid injuries associated with critical operations (e.g., surgery and intensive care). In areas where telephone ring-down systems were being used to alert and notify the public, that system could give advance notice of the need to vacate or ventilate the in-place shelter.

### 8.1.2 Evacuation vs Pressurization

While reduced infiltration in-place shelters generally are less effective than evacuation for lethal exposures, pressurized shelters reduce exposure more effectively than even fairly effective evacuations. Figure 8.5 compares the relative exposure reductions associated with a catastrophic release of GB for a 5- and 10-min clearance of an area, and a pressurized shelter implemented by closing the windows and doors and turning the system on. All of these approaches to protection have the potential to completely eliminate exposure; however, because of the time it takes to make a decision to warn the public, receive the warning, decide to respond to that warning, and implement the protective measure, expected exposures are near or above the $LCt_{50}$ for adult males in each case.

Hence, to provide acceptable protection from such catastrophic releases of agent, emergency systems will have to reduce the time it takes to get people to implement the action. Examination of Figs. 5.4 and 6.1 indicates that the two principal sources of delay for these systems are the time it takes to detect, assess, and decide to warn the public and the public's decision to respond to the warning message. One way to achieve more rapid response to public warnings is to provide the public with enough information to allow them to confirm the conclusion reached by the officials making the recommendation (Rogers 1989; Leik and Carter 1981; Mileti 1975).

## 8.2 COMPLEMENTARY PROTECTIVE ACTIONS

This section examines the extent to which respiratory protection can be used to complement the protection offered by evacuation and in-place sheltering. The concern here rests principally with the response to releases with relatively short onset times that result in potentially lethal exposures. Unfortunately, the methods employed herein were developed to directly examine independent alternatives. Hence, the examination of complementary protective action alternatives requires some preliminary analysis of the behavioral underpinnings of protection under various alternatives.

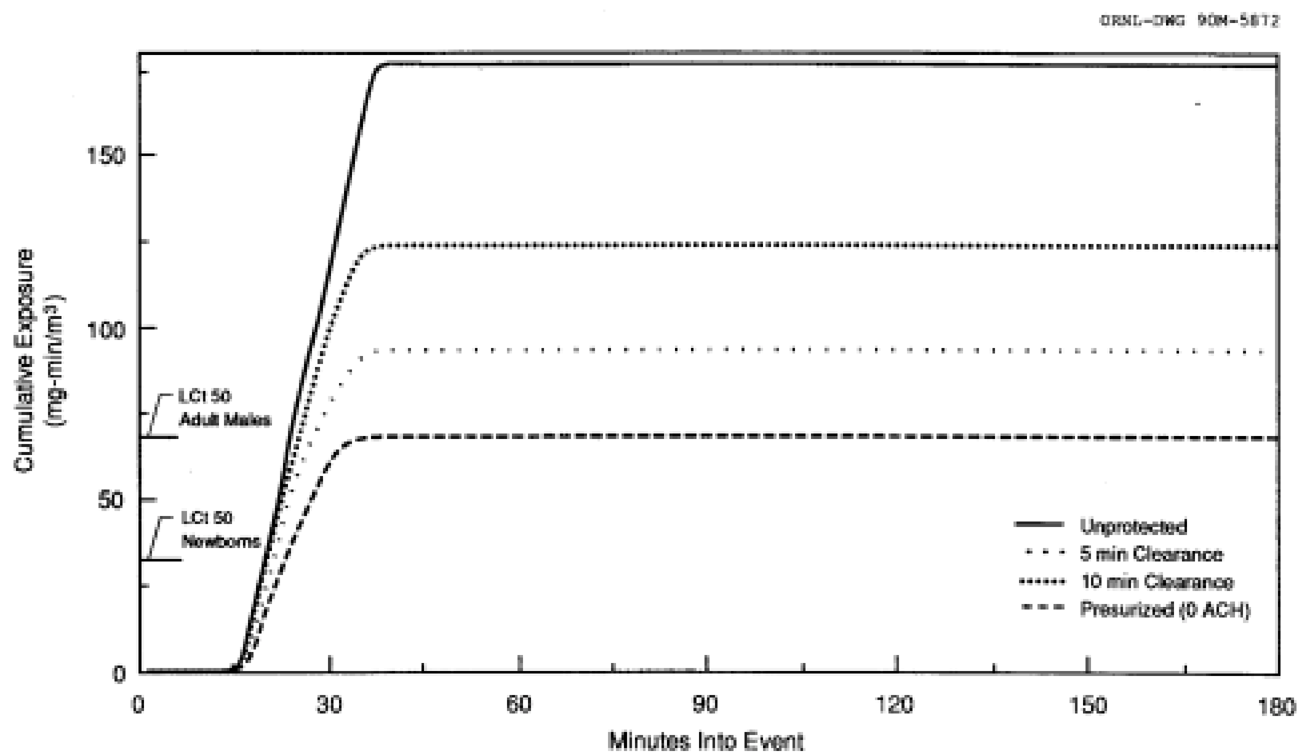


**Fig. 8.5. Comparison of evacuation and pressurized shelter scenarios at 3-km distance for GB class V events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr.

Figure 8.6 presents the probability of completing various aspects of emergency response by the amount of time into the event. There are three fundamental factors in obtaining a completed protective action by the public: (1) the decision to warn and the warning system, (2) the decision by the public to respond to that warning, and (3) the time it takes to implement the selected action. These are represented in Fig. 8.6 as areas A, B, and C through E, respectively. The combined effect of the decision to warn, the warning receipt, and the public's decision to respond is held constant for the goal-oriented analysis presented herein. By examining areas C, D, and E, one can get a sense of the marginal benefit of each protective action. For example, area C may be thought of as the marginal benefit of either reducing evacuation clearance times from 5 min to 1 min or of distributing respiratory protection to people for use while evacuating. Likewise, area D is the marginal benefit of reducing evacuation clearance times from 10 min to 5 min; and the sum of areas C, D, and E is the marginal difference between 1-min clearance evacuations or respiratory protection and expedient sheltering.

The similarities among the implementation curves associated with closing doors and windows and 1-min evacuation or 1-min implementation of respiratory protection (e.g., like having respiratory equipment in cars) imply that exposure differences among these alternatives are principally the result of the protection that the alternatives offer. For example, the difference between in-place shelters and respiratory protection is simply a function of the difference between the exposure associated with a given exchange rate and the exposure associated with leakage and breakthrough. For most release scenarios, the difference is a result of air exchange and leakage rates. The same logic implies that the principal difference between respiratory protection and rapid (e.g., 1-min clearance) evacuation is associated with the seal around a respiratory device. In this sense, in-place protection alternatives characterized by closing doors and windows, respiratory protection, and rapid evacuation all have similar behavioral underpinnings; most of the delays associated with implementation of these protective actions stem from warning receipt and public response. Moreover, because evacuations and pressurized shelters are capable of complete protection and because respiratory protection provides nearly complete protection (except for 15% of the devices employed that leak), the dominant factor in exposure is the behavioral emergency response system (area A and B in Fig. 8.6).

### 8.2.1 Evacuation with Respiratory Protection

Combining the complementary protective actions of evacuation and respiratory protection, the weaknesses of each action are supported by the strengths of the other; evacuation avoids the potential for breakthrough associated with respiratory devices by leaving the area before the breakthrough level is reached. Respiratory devices protect the wearer from evacuating through the plume (e.g., being overtaken by the plume while evacuating). However, it should not be assumed that combining these actions is always preferable, because some types of respiratory protection can obscure vision, making vehicle operation more difficult. Of course, compared with being overcome by the plume, these potential impacts are relatively minor.

Each of the two protective actions have similar root causes associated with their effectiveness. Figure 8.7 presents the expected exposures for 5- and 10-min clearance

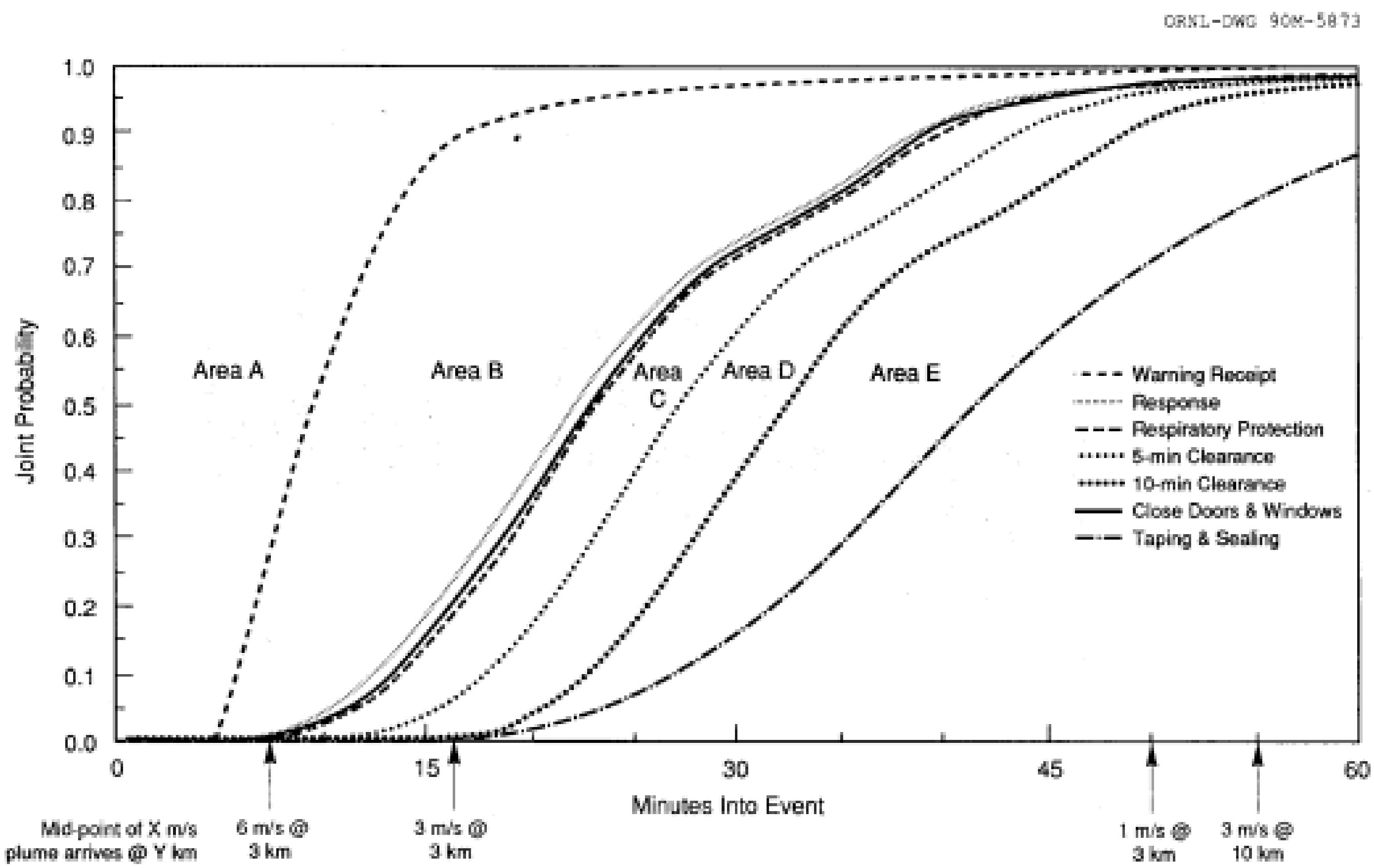


**Fig. 8.6. Probability of completing emergency response functions by time into the event.** Note that goal-oriented emergency response assumptions of 5-min decision to warn, siren and telephone warning system, and public response 25% faster than previous experience.

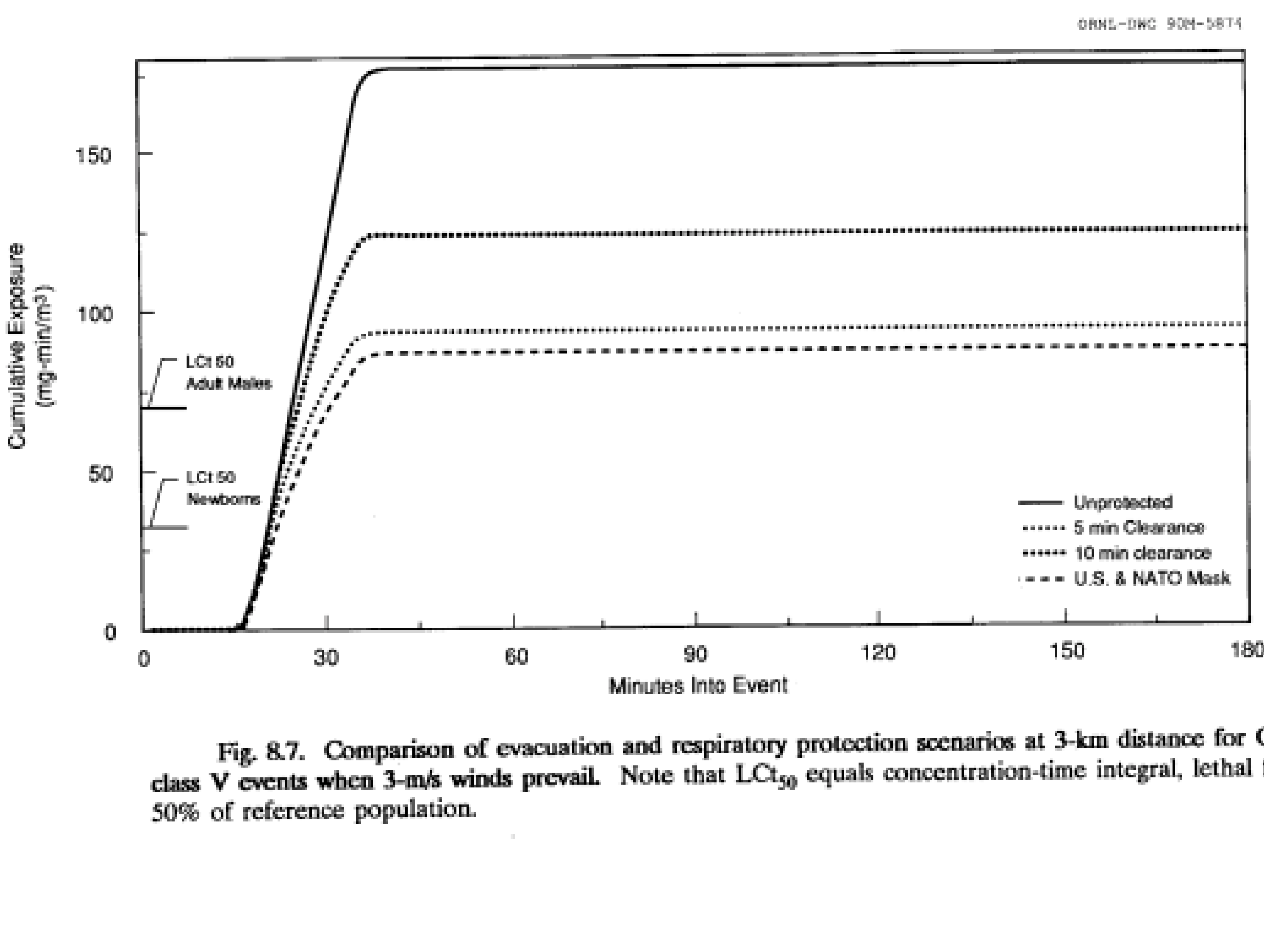


**Fig. 8.7. Comparison of evacuation and respiratory protection scenarios at 3-km distance for Gl class V events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal fo 50% of reference population.

time evacuations and respiratory protection with either the U.S. military or NATO civilian mask in conjunction with a GB Class V event for 3-km distances, with 3-m/s winds. Although these curves do not represent the combined effect of both sets of protective actions, the relative exposures for the 5-min clearance evacuation and those associated with the use of a respiratory device are indistinguishable given the uncertainty in the model. In both cases, the actions, when implemented completely, eliminate exposure. They require minimal time to implement; however, they are both predicated on the same detection, assessment, and decision-making system resulting in a decision to warn the public in about 5-min, a siren and telephone warning system, and a public response system that requires concurrence by the public. Hence, the trade-off here is the increased delay in evacuation associated with donning respiratory protection vs the added protection that these devices would provide while the people are evacuating.

Figure 8.8 presents similar results for a VX Class IV event for 3-km distances and 1-m/s winds. In this scenario, the longer onset time associated with the slower wind speed provides time to complete evacuation before arrival of the plume and to completely avoid exposure. Respiratory protection continues to expose people to leakage, although the breakthrough of the NATO civilian devices is likely to be avoided because it occurs more than an hour into the event. Because the exposure associated with evacuation scenarios examined in this instance are the result of not implementing the action, there is little reason to believe that these people would have donned a respiratory device.

Given the marginal benefit of using respiratory devices in conjunction with evacuation in most scenarios, emergency managers may find it more useful to enhance their ability to detect, assess, and make decisions and communicate them to the public to assume rapid implementation of evacuation, than to supply and maintain respirators to the public. Nevertheless, the use of respirators in conjunction with evacuation should be viewed as being potentially viable for catastrophic releases within 10 km if the respirators can be stored in the vehicle to be used in the evacuation, thus reducing implementation time.

### 8.2.2 In-place Shelter with Respiratory Protection

Combining the complementary protective actions of in-place sheltering and respiratory protection, the weaknesses of each action are supported by the strengths of the other. In-place sheltering reduces the potential for breakthrough associated with respiratory devices by reducing the overall concentration of agent in the environment; respiratory devices protect the wearer from increased exposure in the shelter. Because pressurized shelters eliminate exposure, it is unnecessary to consider the use of respiratory devices in addition to pressurized in-place protection, except for use in vacating pressurized shelters.

Figure 8.9 compares the use of reduced infiltration in-place shelters and respiratory devices in response to a GB Class V event for people located at 3-km distance, under 3-m/s winds. This comparison indicates that emergency response behavior (both organizational and individual) is the principal factor in determining exposure. Specifically, the expected exposures associated with enhanced shelters and respiratory protective devices are indistinguishable. Implementation of respiratory protection or in-place

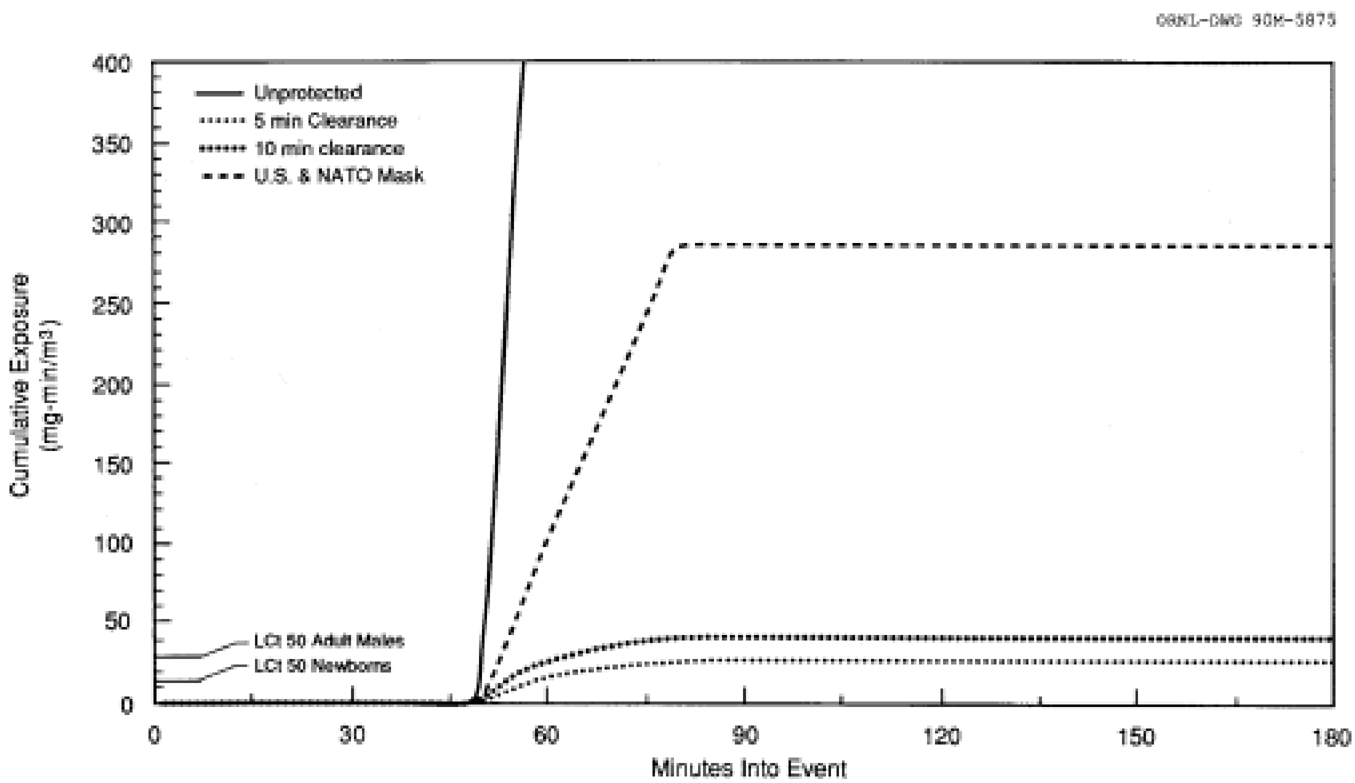


**Fig. 8.8. Comparison of evacuation and respiratory protection scenarios at 3-km distance for VX class IV events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal fo 50% of reference population.

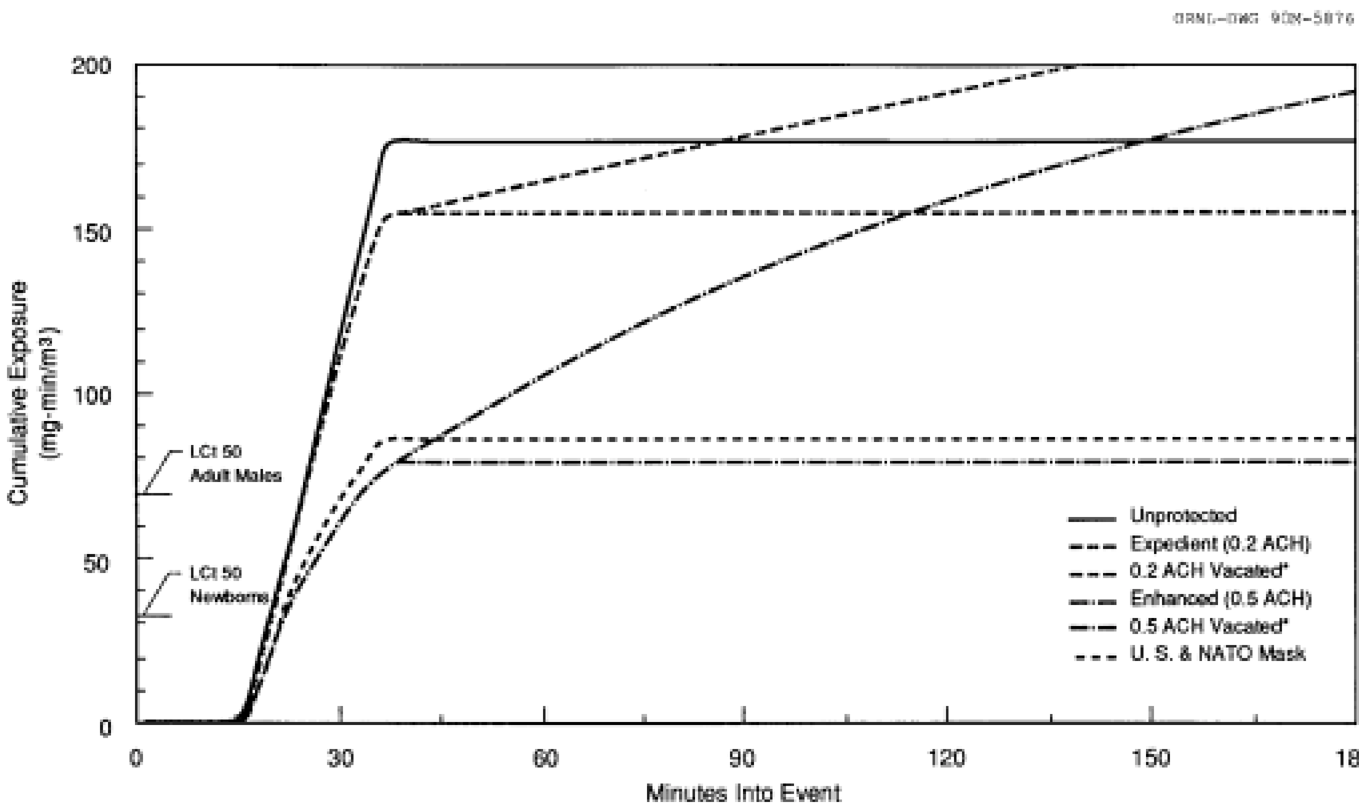


**Fig. 8.9. Comparison of in-place shelter and respiratory protection scenarios at 3-km distance for GB class V events when 3-m/s winds prevail.** Note that $LCt_{50}$ equals concentration-time integral, lethal for 50% of reference population. ACH equals air changes/hr. *Exposure curve is flat after the plume passes because the shelter is vacated when the concentration outside is less than that inside.

protection measures depends on the same emergency response system. Emergency planners could effectively reduce the implementation times associated with in-place protection (e.g., enhancing the seals around a door to an internal room to reduce the amount of time needed to obtain a seal, or recognition of vicarious implementation of in-place shelters in "dead-of-night" hours). Such measures are likely to yield comparable exposures to those obtained by respiratory protection measures.

Figure 8.10 presents similar results for a VX class IV event at a 3-km distance and with 1-m/s winds. In this instance, the implementation of emergency response procedures is more complete because of the slower onset. In this case, it becomes evident that measures to reduce the amount of leakage either into the shelter or around the respiratory device will be required to afford acceptable protection. While combining the actions would reduce exposures to more acceptable levels, pressurized shelters alone or evacuation (Figs. 8.8 and 8.10) are most likely to provide acceptable protection.

Because of the common behavioral underpinnings for the exposures associated with both respiratory protection and reduced infiltration shelters, particularly enhanced sheltering, there is no reason to believe that adding respiratory protection to in-place sheltering significantly reduces population exposure although it should reduce exposure for those implementing both protective actions. Hence, for large releases under rapid onset, pressurized shelters are more likely to provide acceptable protection than a combination of respiratory protection and reduced infiltration shelters. Moreover, when considered in conjunction with the supply, maintenance, and potential liability issues raised by the use of respiratory devices, pressurized shelters are likely to be considered preferable.

## 8.3 IMPLICATIONS, CONCLUSIONS, AND RECOMMENDATIONS

Table 8.1 summarizes the preliminary conclusions associated with this goal-oriented analysis. This research confirms that for the 1.2 million people living more than 10 km but less than 35 km from storage facilities, the preferred protective action is very likely to be evacuation. The analysis of evacuation scenarios for goal-oriented emergency response systems indicates that evacuation is a viable option for people located over 10 km from the source of agent release. This conclusion is generally driven by the amount of time it takes for a release to traverse 10 km (i.e., more than 2.5 h with 1-m/s winds, or approximately 50-min with 3-m/s winds) under moderate and light winds conditions, and by the tendency for agent to disperse significantly in winds of 6 m/s. The amount of time available at this distance generally provides enough time to implement an evacuation.

When situations are characterized by adverse health effects, and an evacuation of the area can be completed before the impact of a plume on an area, evacuation is preferable to in-place shelter alternatives. This arises in part because exposure continues within reduced infiltration in-place shelters after they are fully implemented and in part because such shelters will have to be ventilated or vacated once the plume has passed.

When either long-duration events or very high concentrations are considered, reduced infiltration in-place shelters provide only limited protection. Hence, to the extent possible, evacuation should be used whenever it can be completed before impact or when avenues of egress are clearly not being impacted by the plume. In-place sheltering is most appropriate in those cases where time to respond is severely limited. Pressurized shelters

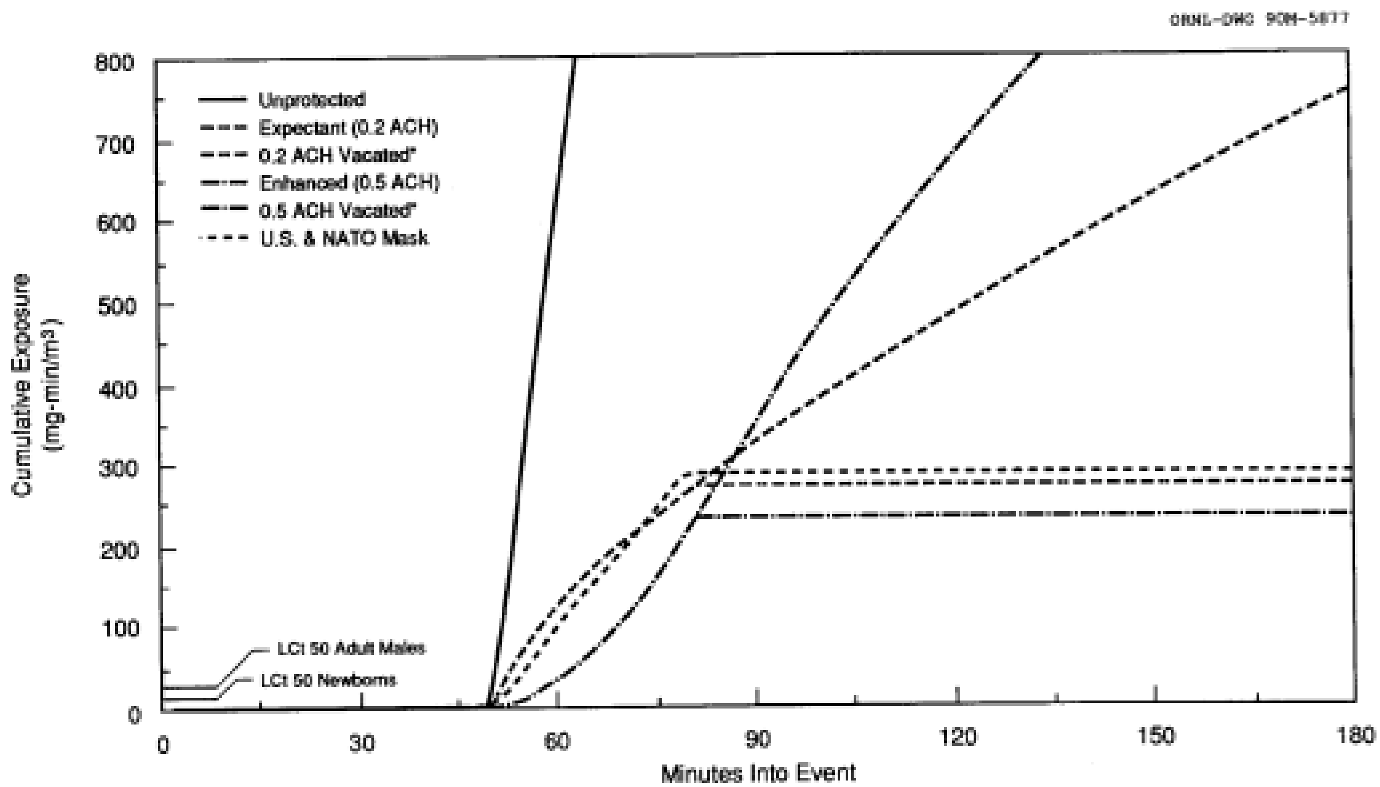


Fig. 8.10. Comparison of in-place shelter and respiratory protection scenarios at 3-km distance fo VX class IV events when 3-m/s winds prevail. Note that $LCt_{50}$ equals concentration-time integral, leth for 50% of reference population. ACH equals air changes/hr. *Exposure curve is flat after the plume passes because the shelter is vacated when the concentration outside is less than that inside.

Table 8.1. Summary of protective action recommendations for the noninstitutionalized public

| Quantity released | Protective action recommendation 1-m/s winds | 3-m/s winds |
|---|---|---|
| | **Less than 5 km distance** | |
| Small | Shelter/Evacuation | NA[a] |
| Medium | Evacuation | Evacuation/ pressurized shelters |
| Large | Evacuation/ pressurized shelters | Pressurized shelters |
| | **5 to 10 km distance** | |
| Small | Evacuation | NA[a] |
| Medium | Evacuation | Evacuation/ respiratory protection |
| Large | Evacuation | Evacuation/ pressurized shelters |
| | **More than 10 km distance** | |
| Small | NA[a] | NA[a] |
| Medium | Evacuation | NA[a] |
| Large | Evacuation | Evacuation |

[a]Not applicable because these releases of GB, VX and H/HD are unlikely to traverse this distance under these winds (see Figs. 4.1, 4.2, and 4.3 and Tables 4.5, 4.6, and 4.7) with exposures exceeding the $LCt_{50}$ for newborn infants.

then provide the maximum protection for people. Enhance shelters also could be used to afford significant protection to people in close proximity; however, in situations

characterized by adverse health effects, it would be inappropriate to recommend using enhanced shelters alone; rather, because of the additional protection afforded by implementing expedient measures within enhanced shelters, the pro-active expedient activities should be undertaken as well.

Moreover, under conditions of relatively minor release, characterized, for example, by release likely to result in reversible health effects, reduced infiltration in-place sheltering can provide significant protection at minimal cost. These benefits are significantly increased when implementation is augmented by the current location of people in indoor locations (e.g., in the dead-of-night). But emergency planners will have to exercise considerable care in recommending such actions so that people can ventilate or vacate the in-place shelters once the plume has passed. Further such measures are probably inappropriate in scenarios where the current minor release may become a long-duration or more extreme one. Hence, emergency managers would be ill-advised to recommend reduced infiltration in-place sheltering when releases are not yet controlled (e.g., where the fire is still burning), or where the plume may become a long-duration event because of meteorological conditions (e.g., during early evening hours when winds may shift or stall).

To the extent that respiratory protection devices are used, emergency planners will have to expend considerable effort to limit exposure associated with leakage around the filtration system of the device. This analysis clearly points out the need to carefully fit people expected to use these devices, undertake considerable maintenance programs to ensure continued viability, and consider the use of respiratory devices that will accommodate a variety of fit/seal problems associated with the general public. It also points out that respiratory protection must be implemented very quickly for it to be considered a viable option.

Emergency managers could even augment each structure's ability to limit infiltration passively by having electrical power turned off in the area(s) likely to be impacted, which would automatically shut down whole-house circulating systems and reduce the amount of infiltration. One consequence of this action, however, would be that warning via electrical devices (e.g., radios and televisions) would be eliminated. In areas where telephone ring-down systems were being used to alert and notify the public, that system could give advance notice of the need to vacate or ventilate the in-place shelter.

To provide acceptable protection from catastrophic releases of agent, emergency response will have to be rapid enough to get people to implement the action. One way to achieve more rapid response to public warnings is to provide the public with enough information to allow them to confirm the conclusion reached by the officials making the recommendation.

With the possible exception of worst-case events, characterized by very large releases under slow onset (1-m/s winds), the marginal benefit of using respiratory devices in conjunction with evacuation may be limited. Emergency managers may find it more useful to enhance their ability to detect, assess, and make decisions and communicate them to the public so that rapid implementation of evacuation can be achieved than to supply respirators to the public and maintain them once they are issued. Moreover, because pressurized shelters eliminate exposure, it is unnecessary to consider the use of respiratory devices in addition to pressurized in-place protection.

The common behavioral underpinnings for the exposure associated with both respiratory protection and reduced infiltration shelters, particularly enhanced sheltering, means that adding respiratory protection to in-place sheltering does not necessarily reduce exposure. Hence, for large releases under rapid onset, pressurized shelters are more likely to provide acceptable protection than a combination of respiratory protection and reduced infiltration shelters. Moreover, when considered in conjunction with the supply, maintenance, and potential liability issues raised by the use of respiratory devices, pressurized shelters are likely to be considered preferable.

## 8.4 FUTURE DIRECTIONS

The conclusions made here are preliminary and subject to much closer scrutiny. The primary purpose of this report was to develop and describe a method for evaluating the effectiveness of various protective actions. The reader should interpret the analyses using the model as illustrations of how the model can be applied. As such, the conclusions provide a springboard for further analyses using the model. Much future work is needed to reach more substantive conclusions, to understand subtleties in relationships, to reduce the large uncertainties in the results, and to find optimum solutions.

The possible paths for future work are numerous and challenging. First, we need to develop better baseline assessments to look at the benefits of alternative protective action strategies. Such baselines could include the current status of emergency systems at the chemical demilitization sites, the adoption of enhanced communications and warning systems, or others as deemed appropriate.

Second, the approach taken is based on a fairly rigid set of assumptions about the performance of human and technological systems. A great deal of sensitivity analysis is needed to understand more precisely how the related aspects of emergency planning are related to different levels of protection.

Third, this report analyzes a limited number of scenarios. One analytic approach would be to develop a database by systematically varying a number of parameters (e.g., both emergency response and release scenario) and use an optimization routine to identify the best protective action option for a given class of scenarios.

Fourth, there is the need to continue to develop the assumptions that underlie the model. This means additional empirical work on documenting decision-making times, warning diffusion, warning response, the exposure reduction offered by protective actions under differing environmental conditions, etc.

Finally, there is the need to refine the model itself and to make it more robust. The first step is to provide a spatial definition to the model. The current version looks at a single point in space. There is a distinct need to allow the user to look at the larger picture that will emerge when the model can integrate data from a large number of points and provide a spatial distribution of exposure reduction from any given scenario. Adding the capability to interface the model with site-specific data, including population distribution or meteorological conditions, is a step in this direction.

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# APPENDIX A

# PROTECTIVE CLOTHING

# APPENDIX A

## PROTECTIVE CLOTHING

Protective clothing is defined here as full-body protection that safeguards against direct skin and eye contact with chemical agents and affords respiratory protection (usually a full-face mask). The principal goal of the various protective clothings designs is to provide individual protection from agent splash, droplet, or aerosol ("liquid") exposure. For example, the estimated percutaneous $LCt_{50}$ in man (clothed and masked) for VX aerosol is 300 mg-min/m$^3$ (0 mph windspeed), in contrast to the estimated percutaneous $LCt_{50}$ in man (also clothed and masked) of 3600 mg-min/m$^3$ (1-mph windspeed) for VX vapor (Krackow 1956, as quoted in Fielding 1960; U.S. Department of the Army 1974). Percutaneous aerosol exposure is clearly more potent by approximately 1 order of magnitude. Reducing the adverse effects of vapor exposure is a function of the degree of respiratory protection because vapor is not readily absorbed through the skin.

Protective clothing may be of two major types: specialized and expedient. Specialized protective clothing has been designed for use by soldiers and military support personnel on the chemical battlefield. Fabrics and overcoverings are treated with, or composed of, special materials that reduce breakthrough. Charcoal-impregnated liners may also be incorporated to absorb any agent that breaches the outer layer. U.S. Army "Level A" clothing is comprised of the M3 toxicological agent protective coverall suit; an M3 hood; butyl rubber safety-toe boots; butyl rubber gloves (worn over surgical or equivalent gloves in a VX/GB area; this second pair of gloves is optional in a mustard area); innerwear (coveralls or fatigues plus drawers, undershirt, and socks for a GB/VX area; impregnated gloves, socks, and long underwear or liner, as well as shirt and trousers for mustard area); and an M9, full face mask. When environments to which personnel might be exposed meet or exceed concentrations considered immediately dangerous to life or health, air-supplied or self-contained suits are authorized (USAMC 1987). "Level A" clothing clearly provides protection to the wearer in areas where the potential for contamination with undiluted agent is high, such as agent spill clean-up or handling of leaking chemical munitions. "Level B" clothing includes an agent protective apron (MS) extending to below the boot tops, coveralls (with drawers, undershirt, and socks; in mustard areas, impregnated underwear, socks, fatigues, and a protective liner are also included); hood; butyl rubber gloves (with same inner glove recommendations as for "Level A" clothing); butly rubber safety toe boots; and an M9 or M17 full-face mask (USAMC 1987). "Level B" clothing is designed to protect the wearer from secondary contamination, such as is possible during medical treatment of a chemical casualty. Trained soldiers can don Level A or B gear in less than 8 min; a "green" recruit requires 6 to 12 h of training before reaching this level of proficiency (Parham 1989). A second person is usually necessary to check for full seam closure.

Expedient protective clothing involves protecting skin from liquid agent exposure by dressing in layers of clothing with long sleeves and long pants; protecting the head and neck with a hood, rain hat or draped towel; protecting hands with rubber gloves; and protecting feet with plastic or rubber footwear (footwear with uppers sewn to soles should

be avoided). The donning of expedient protective clothing will do little to protect from vapor exposure but could provide valuable short-term protection from liquid contamination while the wearer is making his or her way to a shelter or decontamination facility. At the mass care facility, all potentially contaminated clothing will have to be discarded to prevent off-gassing and secondary contamination. Expedient clothing cannot provide protection from inhalation or ingestion exposure. It is reasonable to assume that donning expedient protective clothing will require slightly more time than getting dressed under normal circumstances. Sorensen (1988) estimates that from 5 to 10 min is a reasonable approximation, depending on complexity. Minimum implementation time is about 5 min.

Off-post contamination from spilled liquid or agent droplets ("splash") is considered unlikely; pertinent accident scenarios involve detonation of rockets, 4.2-in. mortars or 105-mm cartridges (the "fireworks scenario") to hurl the munition off-post, where it ruptures on or before contact with the ground (see Table A.1). Warning time for an accident of this type will be very short, if any. Donning any kind of protective clothing requires time that would be better spent in taking shelter or moving away from the impact site. The "fireworks scenario" represents a situation where pausing to dress in protective clothing could actually increase, rather than decrease, the public's risk of exposure. In all "fireworks" cases examined, droplet, or spill contamination would occur most frequently on-post, where specialized protective clothing is considered to be readily available. Estimation of deposition velocity (McMahon and Denison 1979) for a 1000µ diameter droplet (10 mg of VX, the approximate $LD_{50}$ exposure for an adult, would be contained in a droplet of this diameter) and a windspeed of 10 m/s (high windspeed) indicates that all droplets of concern will reach the ground within 500 m of the point of origin provided the initial height of the point of droplet release is less than or equal to 50 m. If the droplet height is less than or equal to 100 m, all droplets will reach the ground within 1 km of the point of origin. Thus, liquid contamination from an on-post rupture and subsequent spray of agent droplets will be largely confined within post boundaries.

In the event of an off-post spill or droplet contamination (rocket, mortar, or cartridge hurled off-site), the Office of the Program Manager for Chemical Demilitarization recommends that post personnel be dispatched to secure the contaminated area and initiate decontamination procedures. Contaminated casualties may be taken off-post for treatment, in which case local health care providers should be sufficiently trained and equipped to decontaminate and treat casualties while wearing "Level B" protective clothing.

The site-specific composition of the unitary stockpile precludes the possibility of a "fireworks" incident at sites that have no munitions in storage. Since ton containers are the only form of unitary storage at Aberdeen Proving Ground (APG) (HD) and Newport Army Ammunition Depot (NAAP) (VX), off-post droplet or spill contamination during incineration disposal is not considered likely at these two installations.

Table A.1. Conditional probabilities of off-post liquid agent contamination given that an accidental detonation of unitary munitions containing propellant has occurred

| Site | Rocket (115 mm) VX | Rocket (115 mm) GB | Cartridge (105 mm) GB | Cartridge (105 mm) mustard | Mortar (4.2 in.) mustard |
|---|---|---|---|---|---|
| ANAD[a] | Possible[b] | Possible[b] | Extremely Low[c] | Extremely Low[c] | Low[d] |
| APG[a] | NA | NA | NA | NA | NA |
| LBAD[a] | Possible[b] | Possible[b] | NA | NA | NA |
| NAAP[a] | NA | NA | NA | NA | NA |
| PBA[a] | Possible[b] | Possible[b] | NA | NA | NA |
| PUDA[a] | NA | NA | Extremely Low[c] | Extremely Low[c] | Low[d] |
| TEAD[a] | Possible[b] | Possible[b] | NA | NA | Low[d] |
| UMDA[a] | Possible[b] | Possible[b] | NA | NA | NA |

[a]Anniston Army Depot (ANAD); Aberdeen Proving Ground (APG); Lexington-Blue Grass (LBAD); Newport Army Ammunition Plant (NAAP); Pine Bluff Arsenal (PBA); Pueblo Depot Activity (PUDA); Tooele Army Depot (TEAD); Umatilla Depot Activity (UMDA).

[b]The M55 115-mm rockets are packed in a fiberglass shipping tube that could act as a firing tube should the propellant be ignited. While the flight of an ignited rocket is likely to have a random trajectory, it could go beyond the installation boundary. Hence, off-post contamination is considered possible once inadvertent propellant ignition occurs.

[c]The 105-mm cartridges are packed one round to a fiber container and two containers to a box. The complete projectile assembly is placed (nose in) into the cartridge case with the nose containing the fuze abutting the percussion primer assembly and propellant charge. The cartridge must be turned 180° prior to firing. Hence, off-post contamination is considered extremely low once inadvertent propellant discharge occurs.

[d]The 4.2-in. mortars are packed one round in a fiber container with two containers in a wooden box. The mortars require a launching tube to attain the desired trajectory and velocity. The storage configuration precludes any directional launch in the event of inadvertent propellant ignition. Hence, off-post contamination is considered low once inadvertent propellant ignition occurs.

The arguments thus far regarding the use of protective clothing in cases of liquid spill or droplet contamination are summarized as follows:

1. Off-post contamination from agent in liquid spill or droplet form is considered unlikely; the public's need for protective clothing to reduce skin exposure from liquid agent is slight.
2. Warning time for such an event will be very short, if any. The time necessary to don protective clothing would be better spent in taking shelter or moving away from the impact site.
3. Approximately 6 to 12 h training are needed to don specialized protective clothing properly and quickly (within less than 8 min).
4. Off-post contamination from agent in liquid spill or droplet form is not considered reasonably likely at APG or NAAP (unitary stockpile at these facilities is not in munition form).
5. Contaminated casualties may be taken off-post for medical treatment, in which case local health care providers should be sufficiently trained and equipped to decontaminate and treat chemical casualties while wearing appropriate protective clothing.

Aerosols are a separate concern from that of liquid spill or droplet contamination. Energetic release (involving a fire or explosion) can generate aerosols (suspension in air of liquid particles between 1 and a few µ in diameter), which may be lofted and transported off-site by wind. Literature values for experimentally generated VX aerosols include particle diameters of 5 or 15 µ (Krackow 1956, as quoted in Fielding 1960). For the 5 µ particle, estimation of deposition velocity (McMahon and Denison 1979) with windspeeds of 3 m/s (conservative most likely windspeed) and 10 m/s (high windspeed) allow us to estimate approximate transport distance with time. The estimates in Table A.2 are not precise, but serve to provide a relative comparison for particles of various diameters that may be explosively released at heights greater than 0.5 m. At release heights less than 0.5 m, Brownian motion and turbulent diffusion become critical factors and require the use of different approximation techniques (McMahon and Denison 1979).

At 1000 s (16.7 min) and an initial particle height of less than or equal to 1 m, nearly all 5 µ aerosol particles would reach the ground within 3 km (at 3-m/s windspeed) or 1.0 km (at 10-m/s windspeed) from the origin. At 3000 s (50 min) and an initial particle height of less than or equal to 3.0 m, nearly all 5 µ particles would reach the ground within 9.0 km (at 3-m/s windspeed) or 30 km (at 10-m/s windspeed). The 15 µ particles would settle out much quicker. At 100 s (1.7 min), almost all 15 µ particles with an initial height of less than or equal to 1 m would reach the ground at a calculated maximum distance of 300 m (at 3-m/s windspeed) or 1 km (at 10-m/s windspeed). After 300 s (5.0 min), nearly all 15 µ particles with an initial height of less than or equal to 3 m would reach the ground within 900 m (at 3-m/s windspeed) or 3.0 km (at 10-m/s windspeed). The smaller particles of persistent agent, such as VX or mustard, are of greatest concern. However, the distribution of particle deposition between the point of release and the calculated maximum transport distance is presently undefined.

Table A.2. Distribution (% of total) of droplet sizes from detonation release

| Drop size[a] (μ) | Agent THD | Agent VX |
|---|---|---|
| 50 | -- | 46 |
| 100 | 30 | 43 |
| 300 | -- | 8 |
| 500 | 41 | 3 |
| 1000 | 24 | -- |
| 5000 | 5 | -- |

[a]These values are presented as upper bounds of the size class. Thus, the 50 μ category includes particles with diameters less than or equal to 50 μ.

*Source*: R. L. zum Brunnen and M. I. Hutton, Chemical Agent Resistant Clothing (CARC) Study, CRDEC-TR-86036, Chemical Research Development, and Engineering Center, Aberdeen Proving Ground, Md., 1986; D. Metz, G. Grove, and M. Hutton, The Handling of Chemically Contaminated Remains, and Personal Effects, DPG/TA-89-008, Technical Analysis and Information Office, U.S. Army Dugway Proving Ground, Dugway, Utah, 1988.

Limited data characterizing the distribution of persistent agent particle sizes generated during munition detonation indicate that VX particles are most usually found in the smallest size classes (89% of all VX particles observed after detonation were less than 100 μ in diameter). Thickened mustard (THD) particles are generally considered to be larger (greater than or equal to 500 μ) (70% of all THD particles considered; zum Brunnen and Hutton 1986; Metz, Grove, and Hutton 1988). The contamination density ($mg/m^2$, a measure of weapon effectiveness determined by measuring the amount of liquid agent reaching the ground following aerial detonation) associated with these size classes is largely 1-100 $mg/m^2$ for VX particles ≤100 μ and 100–1500 $mg/m^2$ for THD particles greater than or equal to 500 μ (zum Brunnen and Hutton 1986; Metz, Grove, and Hutton 1988).

The mass of aerosol particles is another factor to consider and has bearing on calculation of skin exposures received. Although the smaller particles may be lofted and transported long distances, their combined mass (and, therefore, the resulting exposure) is less than that obtained from exposure to the larger particles. This concept is partly expressed in the few available measurements of the mass median diameter (MMD), the

particle diameter at which 50% of the total mass of the distribution is attained. The mass of all particles with diameters less than or greater than the MMD equals 50% of the entire distribution. For VX, the MMD equals 150 µ (sigma function = 50 µ), while the MMD for THD is 500 µ (sigma function = 50 µ) (M. Myirski, Chemical Research Development and Engineering Center, Aberdeen Proving Ground, Md., personal communication to R. Miller, Energy Division, ORNL, Oak Ridge, Tenn., July 28 and 31, 1989).

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# APPENDIX B

# ON PROTECTION FACTORS

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# ON PROTECTION FACTORS

There are two fundamental problems with the protection factor approach to assessing the effectiveness of various protective actions. First, they focus entirely on the physical attributes of the protective action. And second, they rely on data that is typically not available. This appendix, discusses the measurement problems associated with protection factors based on various aspects of protection, examines the availability of data to support such measurement, and the sensitivity associated with measures of protection factors.

## B.1 MEASURING PROTECTIVE ACTIONS

Conceptually, a protection factor is a measure of the ability of an emergency response to protect individuals from the deleterious effects of that hazard. Hence, protection factors for chemical hazards may be thought of as the ability of given protective actions to reduce impact or avoid exposure.

### B.1.1 Based on Probability

The general conceptual definition of protective factor is

$$P_i = u / P_i,$$

where $P_i$ is the protection factor for action i, u is the hazard faced by or the probability of harm to the unprotected person, and $p_i$ is the hazard faced by or the probability of harm to the person protected with protective action i.

Consider a hypothetical protective device that reduces the exposure by a factor of ten. Hence, on the average, people employing this protective device would be ten times as likely to avoid deleterious effects as those unprotected with the device. For example, if 100 out of every 1000 unprotected people would die without use of the device, then protection with the hypothetical device would result in 10 deaths for every 1000 people. The protective factor could be,

$$P_H = U^f / P_H = (100/1000) / (10/1000) = 10,$$

where $P_H$ is the average protection factor for the hypothetical device, $u^f$ is the average fatality rate for unprotected populations, and $P_H$ is the average fatality rate for protected populations.

However, even for this relatively simple hypothetical case, a number of assumptions are implicit in the formulation. First, it is assumed that the deleterious effect of interest is fatalities. While not an unworthy objective, this assumption would ignore protection from nonlethal effects, such as convulsions or incapacitation (nerve agents), or potential

carcinogenesis (mustard exposure). The second assumption is that no protective measure can provide complete protection. If any protective device provides complete protection (e.g., if use of the hypothetical device resulted in no fatalities), the protection factor is mathematically undefined. While this could be avoided by assuming some extremely small number (e.g., $1 \times 10^{-43}$) in place of zero, such an approach would imply far greater certainty both in the data and in the analysis than is warranted. In fact, it is probably reasonable to assume that all protective actions have nonzero risks associated with their use. The third assumption concerns limits on the detection of deleterious effects. At the minimum, the effect of interest must be measurable; at the maximum, our interest is limited to protective actions that reduce the hazard to the range of nonlethal effects. Fourth, all protective actions, with the possible exception of evacuation, are inherently temporary. Hence, time is embedded in the probability of harm for both protected and unprotected individuals (e.g., the probability of harm over some period of time). Finally, any measure of protection assumes that the probability of deleterious effect for both protected and unprotected populations can at least be estimated.

### B.1.2 Based on Concentration

Consider the operational principle that the largest protection factors result from the greatest reductions in peak exposure. Assuming that peak exposure is directly correlated with agent concentration and that concentrations are measurable, the protection factor becomes operationally defined as

$$P^C_i = u^C / p^C_i,$$

where $P^C_i$ is the protection factor based on concentration of chemical agent for action i, $u^C$ is the maximum concentration of chemical agent for individuals in unprotected areas, and $p^C_i$ is the maximum concentration of chemical agent for individuals protected by action i.

While this formulation could estimate the protection factor for a given action by comparing protected and unprotected concentrations at any point in time, maximum concentrations over a period of time are usually compared. Hence, this formulation is useful when the probability of harm is driven by peak concentrations of chemical agent or when point or instantaneous measurements of agent concentrations are available. While protection factors based on concentrations are completely independent of the nature of each deleterious effect, they are sensitive only to concentration of chemical agent and not to any associated threshold of harm.

### B.1.3 Based on Cumulative Exposure

When harm is correlated with cumulative exposure, the operational principle that protective actions resulting in the smallest exposure have the highest protection factor is more appropriate. Assuming that exposure can be estimated directly, the protection factor

is operationally defined as

$$P^E_i = u^E / p^E_i,$$

where $P^E_i$ is the protection factor based on exposure for action i, $u^E$ is the average (cumulative) exposure received by unprotected individuals, and $p^E_i$ is the average (cumulative) exposure received by individuals protected by action i.

Unlike the protection factors based on concentrations, exposure-based protection factors are not conceptually defined for instantaneous applications; as the instant approaches zero, both cumulative exposures also approach zero. This operational measure is most appropriate when the interest is in cumulative exposure reduction associated with various actions over periods of time. This operational definition has the advantage of being measured in terms of the exposure which is directly interpreted in terms of the deleterious effect. Hence, it is not attributable to any given effect but rather to the entire distribution of deleterious effects.

### B.1.4 Based on Period of Time Protected

When the principal interest in protection is motivated by the time period for which an individual can be protected by a given action, protection factors can be based on the comparison of time periods required to reach a given deleterious effect. Assuming that both protected and unprotected time periods can be measured or estimated at nonzero levels, equivalent protection factors based on time period are expressed as

$$P^T_i = p^T_i / u^T,$$

where $P^T_i$ is the protection factor based on the time period protected by action i, $p^T_i$ is the average time period protected from given deleterious effect by action i, and $u^T$ is the average time period required for generation of the same deleterious effect in an unprotected environment.

While exposure-based protection factors place emphasis on the range of potential effects over a given period of time, protection factors based on time period are cast only in terms of the given deleterious effect. Emphasis is placed on the variation in the period of protection. For events that generate the given deleterious effect instantaneously, protection factors based on time period protected may be mathematically undefined. As with the above example of complete protection with the hypothetical device, "instantaneous" may be cast in terms of an extremely small number. The resulting protection factor is likely to be more sensitive to the selection of that number than to the duration of protection provided by various protective actions. For example, if a given protective device protects for 10 min, setting the instantaneous period at 1 s yields a protection factor of 600, while setting it at 1 min yields a protection factor of 10.

The time when the deleterious effect develops is problematic for some end points. For fatalities, the time of death might be used; however, death occurring several days after initial exposures distort the period of protection. Thus, the lag time between exposure

and death (e.g., from complications) cannot be considered a period of protection. Hence, the end of the protection period has to incorporate the time at which a level of concentration associated with a deleterious effect is attained. Conceptually, the beginning of the "assault" on the given environment is the beginning of the time period of concern. While the beginning of the protected period could be cast in terms of the time of the release (i.e., the initiating event), this would introduce an artificial variance in protection factors for the same protective measure being used at various distances from the source. Another related problem is the degradation of the device itself over a period of use even though no assault is under way (e.g., SCBAs use up the supply of uncontaminated air, and rooms that are sealed to prevent penetration become stuffy after being occupied by groups over a period of time). Therefore, setting the period of protection must be sensitive to both the actual assault on the protected environment and the initiation of the protective action. Examples are the arrival of the leading edge of a plume, or the beginning of SCBA use.

## B.2 DATA AVAILABILITY AND SENSITIVITY

Protection factors measured in terms of these formulations imply that measurements of concentration, exposure, or time are available to estimate these concepts. While exposure, concentration, and even time-exposed data have been linked to various physiological effects, the ability of various protective actions to reduce exposure or increase the protected time period has been established via limited data, analysis, and experiments. Available protocols often involve data extrapolations from experimental animals to humans, and from one protective device to other similar devices. Mathematical models often are used to estimate effects. The limitations associated with data availability implies that small differences between protection factors associated with various protective devices are devoid of meaning. Under any circumstances, the decimal portion of a calculated protection factor is without meaning. The resulting protection factor will have to be interpreted with sensitivity to the degree of uncertainty in the estimates and measures on which it is based.

To the extent that protection factors can be estimated, emergency managers would like to use them to plan appropriate accident response. An underlying assumption is that people will uniformly know how to implement each protective action and that the time required to implement each will be available under all scenarios. In using protection factors, the degree to which the estimate is affected by training and implementation time is critical. For example, how much protection is afforded by a given protective action when less than optimal training is available or implementation times are shorter than those required to fully implement the action? In addition, the extent and ability to appropriately use each protective action is critical to determining the effectiveness of each protective action.

# APPENDIX C

# DESCRIPTION OF PROTECTIVE ACTIONS

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## C.1 SUMMARY OF PROTECTIVE ACTIONS

This appendix summarizes the preliminary evaluation of various protective actions that can be taken without an evacuation. These actions are grouped in two categories: those involving in-place protection and those involving individual respiratory protection. The latter category may be used in conjunction with either evacuation or in-place sheltering.

## C.2 IN-PLACE PROTECTION

### C.2.1 Normal Sheltering

Normal sheltering involves taking refuge before potential exposure in existing, unmodified buildings for the prevention or mitigation of the amount of exposure. This protective action has been used to protect people from radioactive fallout. It has also protected people from toxic chemical releases where relatively small concentrations are involved.

Normal sheltering can partially block exposure by reducing the amount of airborne agent infiltration into the "protected" environment. While no protective action provides complete protection under all conditions, normal sheltering is thought to provide adequate protection under conditions characterized by relatively low agent concentrations and limited exposure times (i.e., small and fast-moving plumes).

Normal sheltering requires people to close windows and doors and shut off ventilation systems that replace indoor air with outdoor air. Once in the sheltered environment, people should remain calm to promote lowered heart and respiratory rates. In addition, once the concentration of agent is lower in the unprotected environment than in the protected environment, the structure will need to be ventilated to minimize exposure. Hence, the warning system must not only communicate when to shelter, it must also communicate when to ventilate.

The principle advantages of normal sheltering are:

1. Normal sheltering requires only existing resources,
2. Normal sheltering requires minimal training and no protective equipment,
3. The median house may be characterized as having approximately 0.7 air changes per hour (Nazaroff et al. 1987, as reported in Chester 1988), which means that the protection factors associated with normal sheltering probably range between 1.3 to 10 depending on the cloud passage time (Chester 1988). Hence, normal sheltering provides minimum protection from exposure in situations where emergency actions are precautionary, or concentrations are low, and cloud passage time is limited.

4. Normal sheltering can be implemented quickly. Sorensen (1988) estimates that it can be accomplished in less than 10 min.
5. Normal sheltering can also serve as a convenient anticipatory step for evacuations by assembling the family unit in one place.

The fundamental disadvantages of normal sheltering are:

1. Normal sheltering provides only limited protection under restricted conditions.
2. If an accident is anticipated to result in low exposure (small concentrations and limited duration) or become more extensive (i.e., higher concentrations or extended duration), evacuation from expedient shelters into a contaminated environment will have to be accomplished.
3. A warning system is required to advise those in shelters when the plume has passed and when it is time to ventilate or vacate the shelter.

### C.2.2 Specialized Sheltering

Specialized sheltering involves taking refuge in commercial tents or structures designed explicitly for collective protection of groups from toxic chemical environments.

Specialized sheltering facilities partially block exposure to chemical agents by reducing the amount of airborne agent infiltration into the "protected" environment. While no protective action provides complete protection under all conditions, specialized shelters are likely to provide adequate protection under conditions characterized by releases resulting in moderate to large concentrations of agent with exposure times between 3 to 12 h (i.e., a slowly travelling plume of any size).

Communication devices will have to be obtained for the sheltered area prior to occupation. Once in the sheltered environment, people should remain calm to promote lowered heart and respiratory rates.

The major advantages of specialized shelters are:

1. Use of specialized shelters reduces air infiltration rates, perhaps even to the point of establishing small, continuous exhaust rates. This means that the protection factors associated with specialized shelters are likely to be greater than those associated with expedient or enhanced sheltering. If air infiltration can be reduced to as few as 1 change in 16 h, the protection factor would range from approximately 5 to 120 (Chester 1988). Hence, specialized sheltering provides maximum protection from exposure in nearly all situations.
2. Specialized sheltering can be implemented fairly quickly once the facilities themselves are available. If we assume that portable shelters of this variety are already built or prepositioned, movement to the prepared shelter would require little preparation time (Sorensen 1988).

3. Specialized sheltering provides maximum protection under almost all conditions. Hence, specialized shelters are capable of preventing fatalities when long or continuous releases of agent are anticipated.
4. Specialized sheltering provides shelter for long periods of time and therefore avoids problems associated with misjudging accident durations and peak concentrations.

Some important disadvantages of specialized shelters include:

1. People in specialized shelters may have family members not in the shelter; distress, conflict, and even breach of containment may result.
2. Specialized sheltering requires that special structures be constructed prior to the emergency.
3. For most people, specialized shelters require limited attention. However, prepositioning or prior construction would involve a certain amount of intrusion into the routine environment.

### C.2.3 Expedient Sheltering

Expedient sheltering involves taking refuge in existing structures that are modified to reduce infiltration by using common resources and materials, such as plastic bags, tape, and wet towels before plume arrives.

While no protective action provides complete protection under all conditions, expedient sheltering is likely to provide adequate protection under conditions characterized by releases resulting in moderate concentrations of agent with exposure times between 1 to 3 h (i.e., the plume is travelling moderately fast and is of medium size). A limited number of experiments regarding the implementation and effectiveness of expedient shelters are described in Appendix F.

Expedient sheltering involves taking refuge in existing buildings, closing windows and doors, shutting off ventilation systems that replace indoor air with outdoor air, taping windows, doors, light sockets, and ventilation outlets, and laying a dampened towel across the bottom of the door to reduce infiltration. Communication devices will have to be obtained for the sheltered area before occupation. Once in the sheltered environment, people should remain calm to promote lowered heart and respiratory rates. In addition, once the concentration of agent is lower in the unprotected environment than in the protected environment, people will have to ventilate the structure to minimize exposure. Hence, the warning system must not only be able to communicate when to shelter, it must also communicate when to ventilate.

The principle advantages of expedient shelters are:

1. Expedient sheltering requires only existing resources, but may be more effective if kits for enhancement, including tape, towels, and perhaps a portable radio, are readily available to potentially affected populations.

2. Expedient sheltering requires limited training and limited resources, resulting in a low level of intrusion of protective equipment to the routine environment.
3. Protection factors associated with expedient shelter are increased with the reduction of air infiltration rates and are likely to be greater than those associated with normal sheltering. If air infiltration can be reduced to 1 air change in 4 h, the protection factor would range from approximately 2 to about 60 (Chester 1988). Hence, expedient sheltering provides low levels of protection from exposure in situations where concentrations are expected to be low to moderate, and cloud passage time is limited to the 1 to 3 h range.
4. Expedient sheltering can be implemented fairly quickly. Sorensen (1988) estimated that taping and sealing an average room can be accomplished in 10 to 15 min. The results of limited trials conducted for this research found that expedient sheltering could be completed in about 20 min on average (Appendix F).

The key disadvantages of expedient shelters are:

1. Expedient sheltering provides moderate protection when plumes are of limited size. Hence, expedient shelter will not prevent fatalities when long or continuous releases of agent are anticipated.
2. If accidents anticipated to be of limited duration develop into more extended exposures, the expedient shelters will have to be evacuated in a contaminated environment.
3. The warning system is required to advise those in shelters when the plume has passed and it is time to ventilate or vacate the shelter.

### C.2.4 Pressurized Sheltering

Pressurized sheltering involves taking refuge in existing structures that are capable of being pressurized to reduce infiltration of toxic vapors. This protective action is expected to provide adequate protection under conditions characterized by releases resulting in moderate to large concentrations of agent with exposure times of 3 to 12 h (i.e., a slowly travelling plume of any size).

Pressurized sheltering involves taking refuge in existing buildings, closing windows and doors, shutting off ventilation systems that replace indoor air with unfiltered outdoor air, and starting a pressurization system that uses filtered air to create pressure in the sealed structure. Communication devices will have to be obtained for the sheltered area prior to occupation. Once in the sheltered environment, people should remain calm to promote lowered heart and respiratory rates.

The principle advantages of pressurized shelters are:

1. Pressurized sheltering requires only that existing structures be augmented by pressurization systems.

2. For most people, pressurized shelters require limited attention before the emergency. They provide a low level of intrusion in the routine environment.
3. Pressurized shelters reduce air infiltration rates, perhaps even to the point of establishing small exhaust rates, which drastically reduces the risk of agent exposure. Protection factors associated with pressurized shelters are likely to be greater than those associated with expedient or enhanced sheltering. If air infiltration can be reduced to as little as 1 change in 16 h, the protection factor would range from approximately 5 to about 120 (Chester 1988). Hence, pressurized sheltering provides maximum protection from exposure in nearly all situations.
4. Pressurized sheltering can be implemented fairly quickly. Sorensen (1988) estimates that activating an existing pressure system will take about 5 min.
5. Pressurized sheltering provides maximum protection, under almost all conditions. Hence, pressurized shelters are capable of preventing fatalities when long or continuous releases of agent are anticipated.
6. Pressurized sheltering provides shelter for long periods of time and thereby avoids the problems associated with misjudging accident durations and atmospheric concentrations.

The principle problem with pressurized sheltering is that people in pressurized shelters may have significant others (i.e., family members, friends, neighbors or more distant relatives) not in the shelter; distress, conflict, and even breach of containment may result.

### C.2.5 Enhanced Sheltering

Enhanced sheltering involves taking refuge in structures in which infiltration has been reduced through weatherization techniques. This protective action is expected to provide adequate protection under conditions characterized by releases resulting in moderate concentrations of agent with maximum exposure times between 1 to 3 h (i.e., a medium-sized plume is travelling moderately fast).

Enhanced sheltering involves taking refuge in existing weatherized buildings possessing reduced infiltration rates for energy efficiency, closing windows and doors, and shutting off ventilation systems that replace indoor air with outdoor air. Communication devices will have to be obtained for the sheltered area prior to occupation. Once in the sheltered environment, people should remain calm to promote lowered heart and respiratory rates. In addition, once the concentration of agent is lower in the unprotected environment than in the protected environment, people will have to ventilate the structure to minimize exposure. Therefore, the warning system must not only be able to communicate when to go to shelters of this kind, they must also be capable of communicating when to ventilate.

The advantages of enhanced sheltering are:

1. Enhanced sheltering requires that existing resources be enhanced in much the same way that they would be for energy conservation.
2. Enhanced sheltering requires limited training and limited additional resources, and for most people it would not be recognizably different from a routine environment. This means that a low level of intrusion of protective equipment in the routine environment is associated with this protective action.
3. Protection factors associated with enhanced sheltering are increased with the reduction of air infiltration rates. This means that the protection factors associated with enhanced sheltering are likely to be greater than those associated with normal sheltering. If air infiltration can be reduced to 1 air change in 4 h, the protection factor would range from approximately 2 to about 60 (Chester 1988). Therefore, enhanced sheltering provides limited protection from exposure in situations where concentrations are expected to be low to moderate, and cloud passage time is limited to the 1 to 3 h range.
4. Enhanced sheltering can be implemented very quickly. Sorensen (1988) estimates that the required action could be accomplished in less than 10 min.

The principle disadvantages of enhanced sheltering are:

1. Enhanced sheltering provides moderate protection under conditions where plumes are of limited size. Hence, enhanced shelter will not prevent human health effects when long or continuous releases of agent are anticipated.
2. If accidents anticipated to be of limited duration develop into more extended exposures, evacuating the expedient shelters in a contaminated environment will have to be accomplished.
3. The warning system is required to advise those in shelters when the plume has passed and it is time to ventilate or vacate the shelter.

## C.3 RESPIRATORY PROTECTION

### C.3.1 Respirators

Respirators with filters, or filtering materials, remove airborne toxic compounds prior to inhalation. A wide variety of face mask designs are available commercially, with most being targeted for industrial use (Figs. C.1.A, and C.1.B).

The full face respirator is comprised of a face-covering shield connected to a filter or filter cartridge. Full face respirators are typically regulated to maintain one direction air flow through the filters. By covering the whole face these designs keep the eyes, nose, and mouth clear of contamination. Chester (1988) estimates that full-face respirators are capable of providing a respiratory protection factor of about 2000. However, the principal limiting factor of the mask is the integrity of the seal between the mask and the face.

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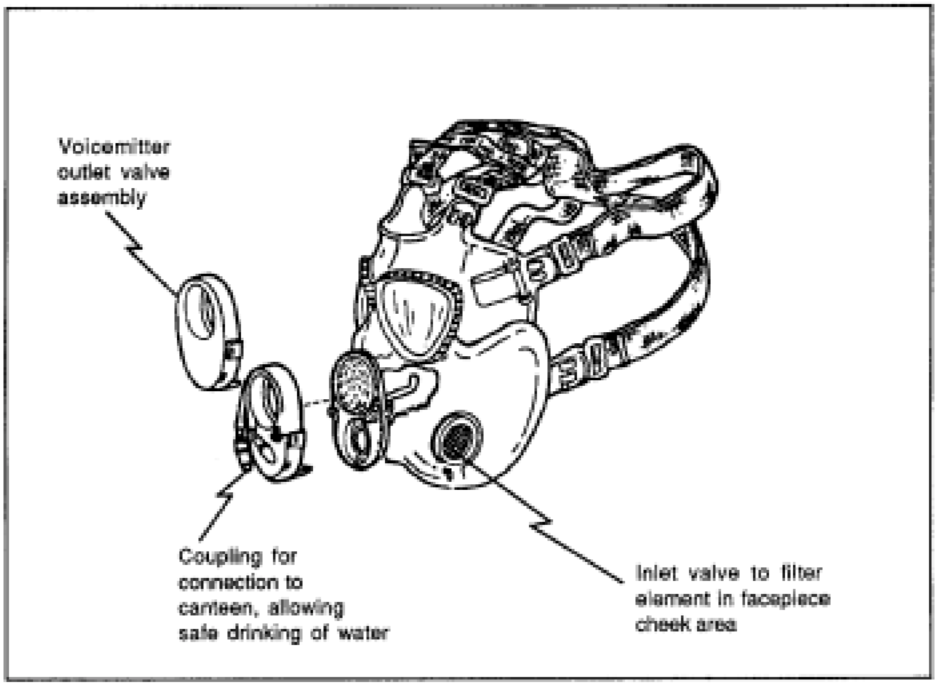


**Fig. C.1.A. Exploded view of U.S. issue standard M17 series mask for troop protection from chemical/biological agent exposure.** See U.S. Department of the Army, Headquarters, *Operator's Manual for Mask*, TM 3-4240-279-10, Chemical Biological: Field, 1987.

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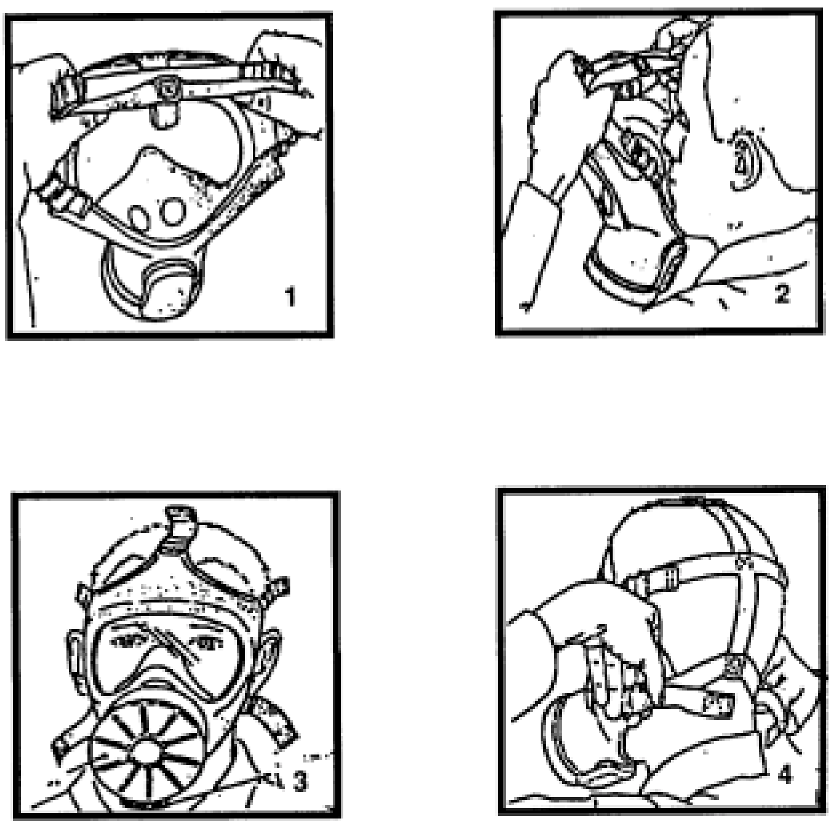

Fig. C.1.B. **Implementation steps for gas mask type 33.** See Forsheda AB, *Gas Mask (type 33)-Technical description*, Forsheda, Sweden, 1987; Trelleborg AB, *Protective Mask (type 33)*, manufacturer's brochure, S-23181, Protective Products Division, Trelleborg, Sweden, 1987.

Using the full face respirator involves retrieving the device from its storage location, extracting it from its storage container, placing on the face, and strapping it in place (see Fig. C.1.B). While this design may take as much as 10 min to implement, Sorensen (1988) estimates that, with training, it can be implemented in as little as 1 min once it is located. The full face mask is very likely to provide respiratory protection from low to moderate concentrations of toxic compounds, but may also be used for protection from larger exposures while people pursue other protective actions (e.g., while evacuating or seeking shelter). Because the full face respirator is an obtrusive device in use, distributing it to the public is likely to raise awareness and could significantly contribute to public concern.

The principle advantages of a full face respirator are:

1. The full face respirator is storable in locations where use is likely.
2. This protective action can be implemented in as little as a minute once it is located; however, moderate training and considerable practice are required.
3. The full face respirator provides a high degree of respiratory protection.
4. The full face respirator requires little physical effort or mental concentration to maintain the seal between face and mask once it is in place.

The disadvantages of the full face respirator are:

1. The full face respirator requires moderate training and practice to assure proper use in emergencies.
2. Use of this protective action would require that the individual have the device, be able to retrieve it, and know how to use it in the event of an accident.
3. The full face respirator must be easily retrieved in an emergency. Because it also must be fully functional once retrieved, it may need to be isolated from potential sources of degradation (e.g., crushing, humidity); storage requirements make the device somewhat obtrusive.
4. It would not protect guests and visitors.

### C.3.2 Hoods

Hoods with fan-driven filters may be placed over the head and sealed at the waist and wrists to remove contaminated air prior to inhalation (Fig. C.2). They are typically used for respiratory protection for children or when the size or shape of the face makes maintaining the integrity of the seal between face and mask nearly impossible. Hoods are typically regulated to maintain one direction air flow through the filters. By covering the whole head and upper body, hoods are designed to keep the eyes, nose, and mouth clear of contamination, as well as affording protection of the upper body from agent deposition. It might be anticipated that hoods, like masks, are capable of providing a respiratory protection factor of about 2000, however, because hoods maintain a constant flow of air into the device maintaining a slight pressure, the protection factor will be reduced. Considering that people exhale once for each inhalation, it can be anticipated that the

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**Fig. C.2. Protective jacket and hood for children.** See Trelleborg AB, *Protective Jacket (type 36)*, manufacturer's brochure, S-23181, Protective Products Division, Trelleborg, Sweden, 1987; Forsheda Group, *Forsheda, A Worldwide Group of Polymer Companies*, manufacturer's brochure, 33012, Forsheda AB, Forsheda, Sweden, 1987.

filter in a fan driven device is filtering at least twice as much air as a respiration driven device. Hence, hoods equipped with fan driven filters would be expected to have a maximum protective factor of 1000 (Chester 1988). The limiting factor with hoods is the integrity of the seal between the hood and the waist and wrists.

Using hoods involves retrieving the device from its storage location, extracting it from its storage container, placing it over the head, securing the waist and wrists and starting the fan-driven filtered ventilation. While protecting someone with a hood may take as much as 10 min it seems reasonable to estimate that, with training, that time can be reduced to as little as a 3 to 5 min once the unit is located. The limiting factor for time seems to be the ability to "dress" children in the hoods. Hoods are very likely to provide respiratory protection from low to moderate concentrations, but may also be used for larger exposures while people pursue other protective actions (e.g., while evacuating or seeking shelter). Because hoods are fairly obtrusive devices, distribution to the public is likely to raise hazard awareness, and could significantly contribute to public concern.

Hoods with fan driven filters have the following advantages:

1. Hoods are storable in the location where use will be required.
2. Hoods can be put on in as little as a few minutes once they are located. This implementation time will require moderate training and practice.
3. Hoods provide a high degree of respiratory protection.
4. Hoods require almost no physical effort or mental concentration to maintain the seal between waist and wrists and the hood once they are in use.

The disadvantages of hoods are:

1. Hoods require some training and practice to assure proper use in emergencies.
2. Hoods would require that the individual have the device, be able to retrieve it, and know how to use it in the event of an accident.
3. Hoods must be easily retrieved in an emergency. They also must be fully functional once retrieved, therefore, they should be protected from potential sources of degradation (e.g., crushing, humidity, cracking, or tearing of the protective membrane); storage requirements make the device somewhat obtrusive.
4. Hoods would not protect guests and visitors.
5. Fan-driven models require batteries.

### C.3.3 Bubbles

Bubbles are sealable containers, with a fan-driven filter, that require the individual to be placed in the protected environment. They are typically used for protection of infants and toddlers (Fig. C.3).

These protective enclosures are comprised of a protective covering ventilated through either battery-operated fan-driven filters or by being connected to an adult's

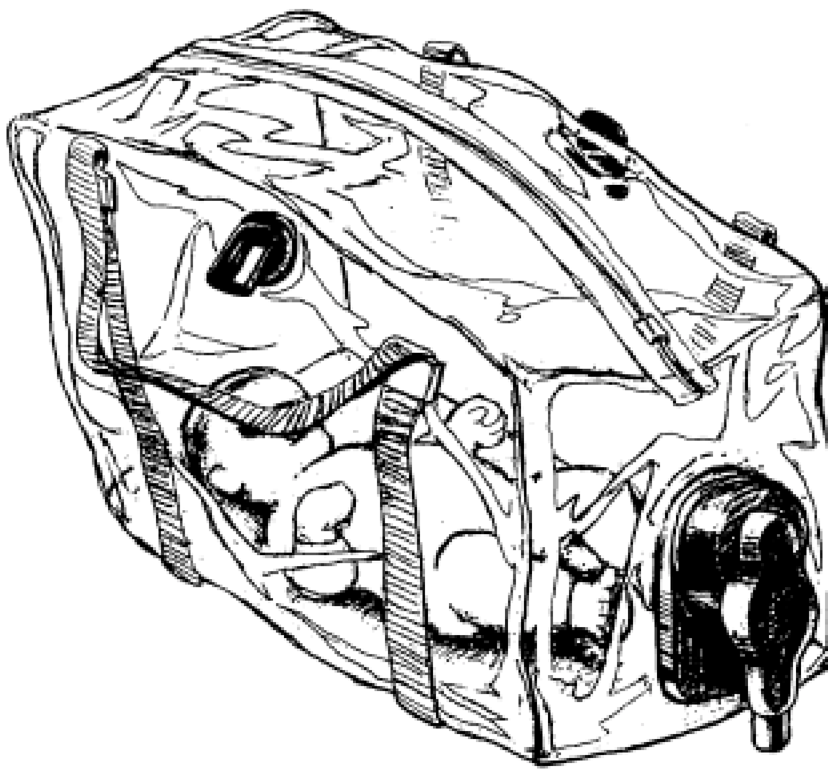


**Fig. C.3. Protective bubble for infants.** See Trelleborg AB, *Protective Baby-lift (type 39)*, manufacturer's brochure, S-2318, Trelleborg AB, Protective Products Division, Trelleborg, Sweden, 1987.

protective device, which draws air through the filter into the infant enclosure. By covering the child's body, bubbles are designed to keep the child's eyes, nose, and mouth clear of contamination, as well as affording protection to the skin. While it is anticipated that protection bubbles will have the same filters as other masks which are capable of providing a respiratory protection factor of about 2000 (Chester 1988) fan-driven devices reduce overall protection Like protective hoods, bubbles require the fan-driven filter to maintain a slight pressure from within the device. Hence, if the occupant inhales half the time the protection factor would be about 1000, but maintaining a slight pressure probably reduces the protection factor below 1000. Protection factor may be as low as 500.

Using the fan-driven protection bubbles involves retrieving the device from its storage location, extracting it from its storage container, placing the infant or toddler in the enclosed environment, and starting the fan-driven filtered ventilation. While a protection bubble may take as much as 15 min to implement, it seems reasonable to estimate that, with training, implementation time can be reduced to as little as 5 to 10 min once the device is located. Protection bubbles are very likely to provide respiratory protection from low to moderate concentrations, but may also be used for larger exposures while people pursue other protective actions (e.g., while evacuating, or seeking shelter). Because protection bubbles are fairly obtrusive devices, distributing them to the public is likely to raise hazard awareness, and contribute to public concern.

Protection bubbles have the following advantages:

1. An infant can be sealed in a protection bubble in as little as a 5 to 10 min once the bubble is located. This implementation time will require moderate training and practice.
2. Protection bubbles provide a high degree of respiratory protection.
3. Protection bubbles require no physical effort or mental concentration to maintain seals.

The disadvantages of protection bubbles are:

1. A protection bubble must be easily retrieved in an emergency. It also must be fully functional once retrieved; during storage, it may need to be isolated from potential sources of degradation (e.g., crushing, humidity, cracking or tearing of the protective membrane); storage requirements make the device somewhat obtrusive.
2. Protection bubbles require some training and practice to assure proper use in emergencies.
3. Protection bubbles would require that the individual have the device, be able to retrieve it, and know how to use it in the event of an accident.
4. Protection bubbles would not protect guests and visitors.
5. Fan-driven models require batteries.

### C.3.4 Mouthpiece Respirator

The mouthpiece respirator is an escape devise comprised of a mouthpiece connected to a filter cartridge by a tube (Fig. C.4). Respiration is limited to the mouth by a nose clip. To gain maximum protection offered by this device the user could put on a transparent hood (e.g., a plastic bag) and exhale through the nose, which would flush the hood with uncontaminated air. This would help keep the eyes clear of contamination. The mouthpiece respirator is intended to be used only for a few minutes while the wearer pursues other protective actions (e.g., evacuation or sheltering). The limiting factor with the mouthpiece respirator is the integrity of the self-maintained seal between the lips and the mouthpiece.

Using the mouthpiece respirator involves retrieving the device from its storage location, inserting the respirator into the mouth, and clipping the nose or covering the head with a transparent hood. The simplicity of the device makes it possible to use this device without training. Chester (1988) estimates that it can be implemented by the untrained user very rapidly, probably in less than a minute once it is located. The mouthpiece respirator requires considerable physical effort and a fair amount of mental concentration to maintain the seal between the lips and mouthpiece. The mouthpiece respirator is most likely to provide reasonable respiratory protection from low to moderate concentrations while people are escaping and pursuing other protective actions (e.g., while evacuating or on the way to shelter). Even though the mouthpiece respirator is fairly unobtrusive, its distribution to the public is likely to raise hazard awareness, and contribute to public concern.

The advantages of the mouthpiece respirator are:

1. The mouthpiece respirator is easy to store in the locations where use might be anticipated.
2. The mouthpiece respirator can be put on in only a few seconds, once it is located.
3. The mouthpiece respirator provides moderate respiratory protection.
4. The mouthpiece respirator requires little training for adequate use.

The primary disadvantages of the mouthpiece respirator are:

1. The mouthpiece respirator requires considerable physical effort and mental concentration to maintain a seal around the mouthpiece.
2. Expedient augmentation of the mouthpiece respirator to achieve eye protection requires some dexterity and concentration, which will likely be difficult for people in the process of pursuing other protective actions.
3. The mouthpiece respirator would require that the individual possess the device and be able to easily retrieve it in the event of an accident.
4. The mouthpiece respirator would not protect guests and visitors unless additional units were available.

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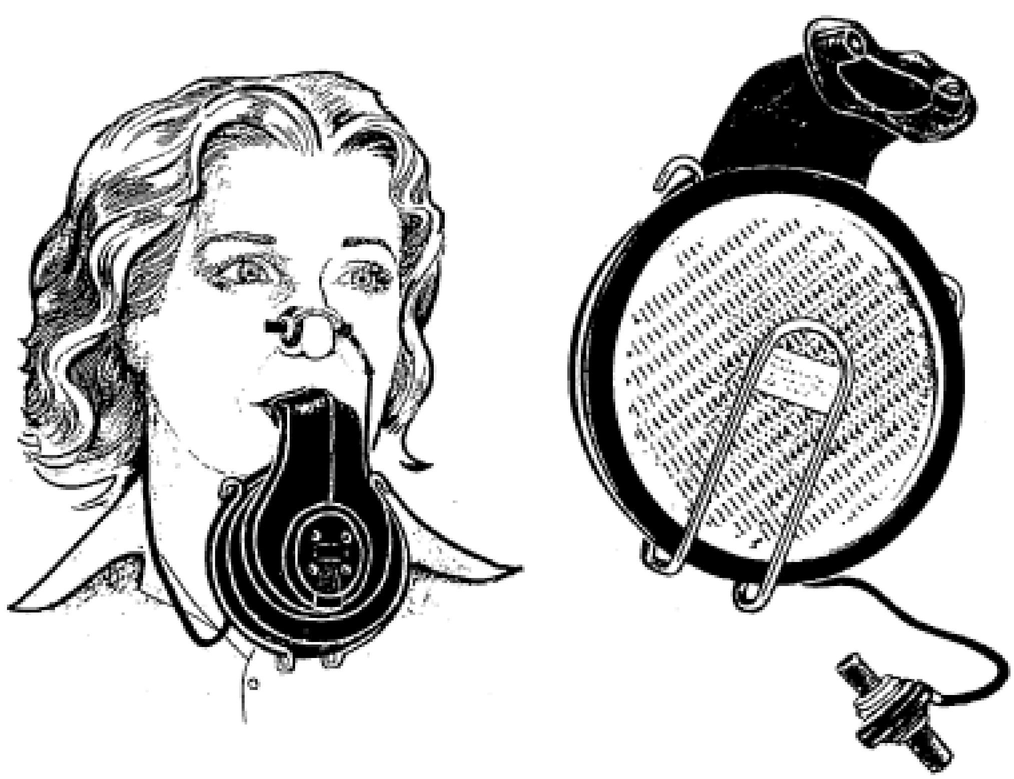

Fig. C.4. Mouthpiece respirator. See Mines Safety Appliance, *Miniguide to Safety and Health Products*, manufacturer's brochure, MSA International, Pittsburgh, 1986.

5. The mouthpiece respirator would have to be replaced by a mask if durations of potential exposure increased to more than 0.5 h.

### C.3.5 Facelet Mask

The facelet mask is a charcoal cloth mask covering the mouth and nose and held on by elastic straps (Fig. C.5). Chester (1988) estimates it would yield maximum theoretical a respiratory protection factor of 1200 against GB, and 80 against mustard. The effects of respiratory moisture and non-uniform flows reduce the amount of protection. An additional limiting factor with the facelet mask is the integrity of the seal between the mask and the face. Taken together, these factors probably limit the protection factor for G agents to under 100.

The user of the facelet mask must retrieve the device from its storage location, extract the mask and its straps from their package, determine how to attach the straps and place the completed assembly over the mouth and nose. While with some limited training and practice the mask might be put on over the nose and mouth quite quickly and held in place with a hand. Chester (1988) estimates that it is likely to take a few minutes to put on the facelet mask. The facelet mask is most likely to provide reasonable respiratory protection from low to moderate concentrations while people are pursuing other protective actions (e.g., while evacuating or seeking shelter). Even though the facelet mask is unobtrusive, its distribution to the public is likely to raise hazard awareness and contribute to public concern.

The principle advantages of the facelet mask are:

1. The facelet mask is easily stored, which means that it is probably the least intrusive respiratory device.
2. The facelet mask can be put on quickly, probably in less than a few minutes.
3. The facelet mask provides moderate respiratory protection from agents GB and mustard.

The disadvantages of the facelet mask are:

1. Using the facelet mask gives a sensation of recycling warm, damp, stale air, which makes it uncomfortable. Absorption capacity is reduced to the extent that the mask becomes saturated with moisture.
2. The facelet mask requires that the individual have the mask, be trained in its use, and be able to retrieve it in the event of an accident.
3. Facelet masks would not protect guests and visitors unless additional units were available.

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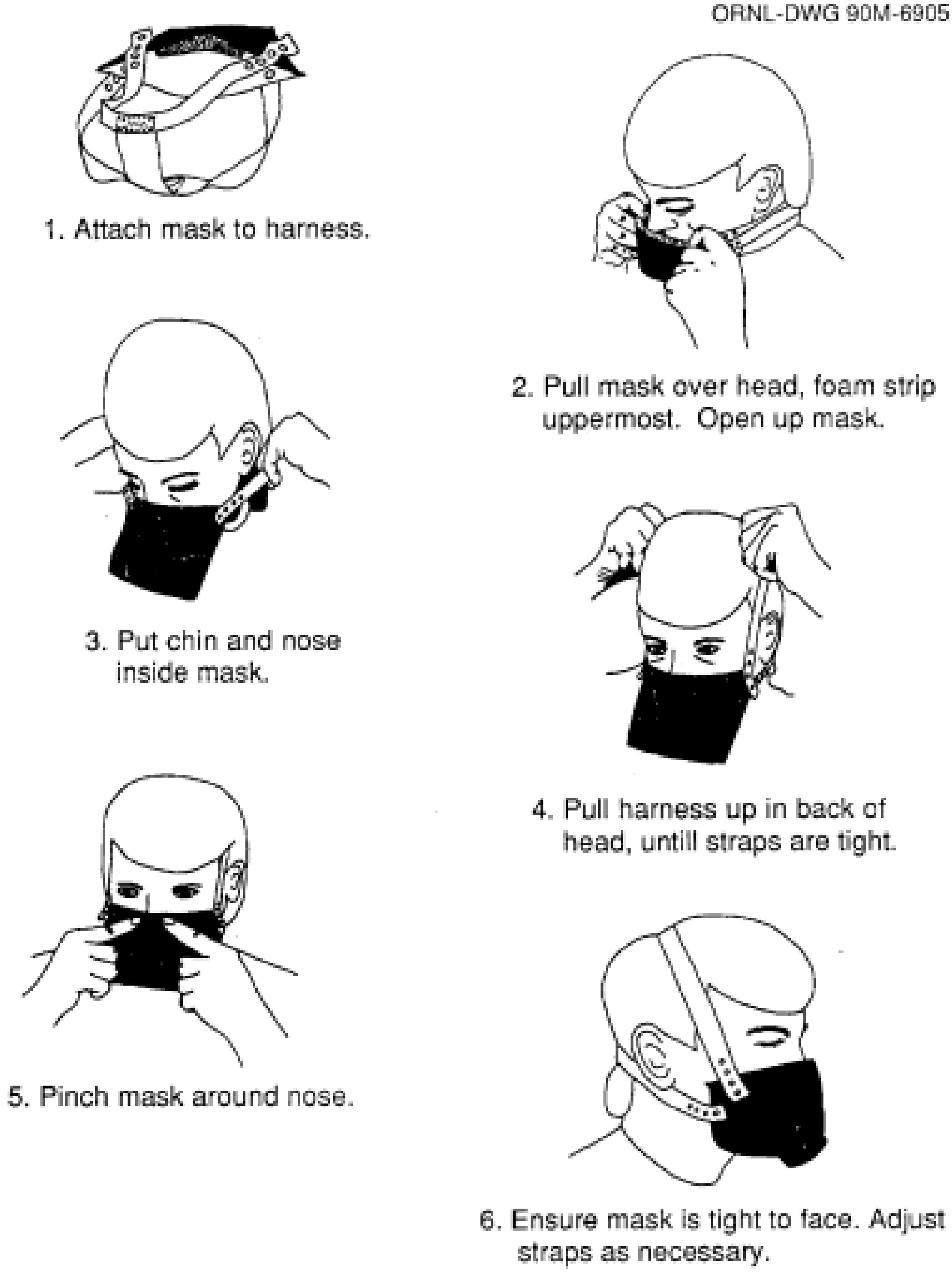


**Fig. C.5 Instruction for filtering charcoal cloth facelet masks.** See Charcoal Cloth, Ltd., *Instructions for filtering charcoal cloth facelet masks*, Charcoal Cloth, Ltd., Park Court, la Park St. Maidenhead, Berks, United Kingdom, 1984.

### C.3.6 Expedient Respiratory

Expedient respiratory protection involves the use of available resources for limited gains in protection against airborne chemicals. A thick cloth (e.g., a wash cloth towel or several thicknesses of cotton handkerchief) covering the mouth and nose is held on the face with a hand. Expedient measure such as this are limited both by their in ability to remove contamination from the area and the difficulty of maintaining the integrity of the covering over the nose and mouth.

Using expedient measures involves gathering the resources required to implement the action and placing the cloth over the nose and mouth.

Tests with aerosols have demonstrated greater than 85% removal efficiencies upon inhalation through 8 thicknesses of a cotton handkerchief or 2 thicknesses of bath towel (Guyton, et al. 1959). No significant increase in removal efficiency was observed when these items were dampened and tested. Greater thicknesses of handkerchief increased breathing resistance to intolerable levels (Guyton, et al. 1959). No training is required for these kinds of measures to be implemented very quickly. Sorensen (1988) estimates that expedient measures can be implemented in a few seconds. Expedient respiratory protection measures are only likely to provide respiratory protection from relatively small concentrations or for a short time while people are pursuing other protective actions (e.g., while evacuating, or seeking shelter).

The principle advantages of expedient respiratory protection are:

1. Expedient respiratory protection is completely unobtrusive.
2. Expedient respiratory protection can be implemented very rapidly, probably in as little as a few seconds.
3. Expedient measures would protect guests and visitors.
4. Expedient respiratory protection provides limited protection from low concentrations for very short durations, probably less than 15 min.

The disadvantages of expedient respiratory protection include:

1. Expedient respiratory protection provides no protection for either moderate or high concentrations, or durations longer than a few minutes.
2. Expedient respiratory measures may be difficult to maintain while pursuing other protective actions (e.g. while evacuating or driving a vehicle).
3. Expedient measures are less effective for vapor than particle exposures.

### C.3.7 Self-contained Breathing Apparatus (SCBA)

Self-contained breathing apparatus (SCBA) provide noncontaminated air for inhalation (Fig. C.6). Bottled air is supplied directly to the individual using it for respiratory protection. Each SCBA is comprised of a tank or bottle of noncontaminated air, attached through a regulator to either a mouthpiece or a full face mask. SCBA

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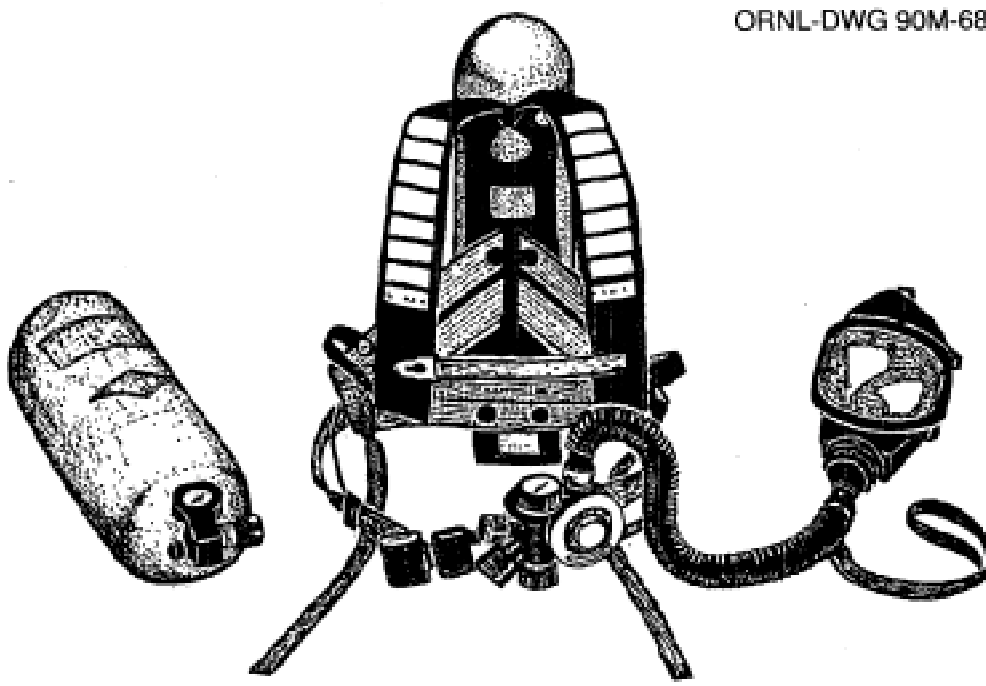

Fig. C.6. Selfcontained breathing apparatus with compressed air source. See Mines Safety Appliance, *Custom 4500II and Ultralite Air Masks*, fact sheet 01-00-11, MSA International, Pittsburgh, 1988; Mines Safety Appliance, *Miniguide to Safety and Health Products*, manufacturer's brochure, MSA International, Pittsburgh, 1986; Siebe Gorman and Company, Ltd., *Compressed Air Breathing Apparatus: Firefighter Escape Sets*, manufacturer's brochure, Siebe Gorman and Company, Ltd., Avondale Way, Cwmbran, United Kingdom, 1985.

equipment that covers the whole face is designed to keep the eyes, nose, and mouth clear of contamination. SCBA units are capable of providing respiratory protection for a period of time governed by the volume of air in the tank and the physical exertion of the wearer. The limiting factor with SCBA covering the face, as with other masks, is the integrity of the seal between the mask and the face. SCBA units without masks are limited by the seal between the mouthpiece and the lips.

Using SCBA involves retrieving the device from its storage location, extracting it from its storage container, placing the mask on the face or the mouthpiece in the mouth, and turning on the air supply valve. While a full face SCBA may take as much as 10 min to implement, training can reduce implementation times to less than a minute once the SCBA equipment is located. SCBA equipment is very likely to provide respiratory protection from moderate to high concentrations, but because of its limited duration of protection (approximately 30 min to 1 h) it is most likely to be useful for people pursuing other protective actions (e.g., while evacuating, or on the way to shelter).

The advantages of SCBA equipment are:

1. SCBA equipment is easily stored at the locations where it is needed.
2. A SCBA can be put on in as little as a minute once it is located. This implementation time will require moderate training and practice.
3. SCBAs provide a high degree of respiratory protection.
4. Face mask SCBA requires little physical effort or mental concentration to maintain the seal between face and mask once it is in use.
5. Some people may already have SCBA equipment specifically designed for underwater use.

The disadvantages of SCBA equipment are:

1. SCBA equipment requires some training and practice to assure proper use in emergencies.
2. SCBAs require that the individual possess the device, be able to retrieve it, and know how to use it in the event of an accident.
3. SCBA would not protect guests and visitors unless additional units were available.
4. SCBA equipment must be easily retrieved in an emergency, therefore must be accessible. It also must be fully functional once retrieved; needs to be isolated from potential sources of degradation (e.g., crushing, punctures or tears in hoses); these storage requirements make the device very obtrusive.
5. SCBAs designed especially for chemical protection are intrinsically a very obtrusive device for respiratory protection. Distribution to the public is likely to raise awareness of the program, and could significantly contribute to public concern.
6. The mouthpiece associated with a SCBA unit requires considerable physical effort or mental concentration to maintain seal once it is in use.

## C.4 PROTECTIVE CLOTHING

Specialized protective clothing is comprised of clothing which will reduce the deposition of chemical agent on the skin by covering the whole head, upper body, arms, legs, feet, and hands with fabric specifically designed to prevent penetration of agent droplets. The limiting factor is the ability to keep all skin covered to prevent contact with agent. Specialized protective clothing is likely to provide protection from skin deposition during releases resulting in moderate concentrations of agent with exposure times between 1 to 3 h (i.e., a medium-size plume is traveling moderately fast).

While specialized clothing can be used to protect against dermal exposure, protective clothing does not protect people from inhalation or ingestion of agent. It is reasonable to estimate that donning protective clothing will require slightly more time than getting dressed. Sorensen (1988) estimates that putting on specialized protective clothing will take between 5 and 10 min depending on its complexity. Using specialized protective clothing involves retrieving and extracting gear from the storage location, putting it on, and checking all seams for closure. While protective clothing may take as much as 10 min to put on, it seems reasonable to estimate that with training, implementation time can be reduced to as little as 3 to 8 min once the clothing is located. Protective clothing is very likely to provide dermal protection from low to moderate concentrations, and may even provide limited protection for larger exposures while people pursue other protective actions (e.g., while evacuating, or on the way to shelter).

The advantages of protective clothing are:

1. Protective clothing is easily stored in preposition locations.
2. Protective clothing can be put on in less than 8 min once located. This implementation time will require some training and practice (approximately 6 to 12 h).
3. Protective clothing provides a high degree of dermal protection.

The disadvantages of protective clothing are:

1. Putting on protective clothing requires some training and practice (approximately 6 to 12 h) to assure proper use in emergencies.
2. Protective clothing would require that the individual have the device, be able to retrieve it, and know how to use it in the event of an accident.
3. Specialized protective clothing would not protect guests and visitors.
4. Because specialized protective clothing is intrinsically very obtrusive, its distribution will raise awareness of the program, and could significantly contribute to public concern.

### C.4.1 Expedient Protective Clothing

Expedient protective clothing is regular clothing that put on to protect the wearer from agent skin deposition. Expedient protective clothing, which can include rain gear, covers the whole head, upper body, arms, legs, feet, and hands with layers of fabric. Expedient protective clothing is limited both by its ability to prevent penetration and keep all skin covered and is likely to provide skin protection under conditions characterized by low concentrations of agent with exposure times of less than an hour (i.e., a fast moving plume of small to medium size).

Expedient protective clothing involves dressing in layers of heavy (winter) clothing with long sleeves and long pants, protecting the head and neck with a hood or draped towel, and protecting hands with gloves. To the extent possible, the outermost layer of expedient clothing should be moisture resistant to help prevent penetration. While expedient clothing can provide limited protection against skin exposure, protective clothing does not protect individuals from inhalation or ingestion exposure. It is reasonable to estimate that putting on expedient protective clothing will require slightly more time than getting dressed in normal clothing. Sorensen (1988) estimates that donning protective clothing will take between 5 and 10 min depending on its complexity. Expedient protective clothing is not anticipated to be very complex, and therefore implementation times are expected to be as little as 5 min.

The advantages of expedient protective clothing are:

1. Expedient protective clothing is completely unobtrusive.
2. Expedient protective clothing can be implemented in as little as 5 to 10 min once the items are located; implementation requires little training and practice.
3. Expedient protective clothing provides a moderate degree of dermal protection for low concentrations for relatively short durations.
4. Expedient protective clothing would use available resources to protect guests and visitors just as it would residents.

The disadvantages of expedient protective clothing are:

1. Expedient protective clothing would require that the individual quickly gather readily available resources, decide how to use them most effectively, and use them for protection.
2. Expedient protective clothing can only protect against dermal exposure.
3. Expedient protective clothing provides limited protection against low to moderate concentrations and would not protect against skin exposure for higher concentrations over extended periods.

## C.5 PROPHYLACTIC DRUGS

"Prophylactic drugs" are used prior to agent exposure for the prevention or mitigation of agent effects. This protective action has been seriously considered only for potential nerve agent exposure.

Pretreatment by drugs that can partially block the effects of these agents on the nervous system offer some degree of protection from incapacitation or death; none provide protection for an unlimited period of time. These findings are largely based on laboratory studies with guinea pigs.

Drugs tested for their pretreatment efficacy include combinations of pralidoxime mesylate, atropine, Valium®, pyridostigmine, physostigmine and aprophen. A combination of pralidoxime mesylate and atropine is available as an autoinjector unit in the United Kingdom and is approved for pretreatment use by Commonwealth military personnel. The United Kingdom protocol calls for oral self-administration of Valium® at the time of intramuscular injection. This combined approach has been successfully tested in guinea pigs exposed to lethal concentrations of either agent GB or agent VX, but is not currently approved for use in the United States. To our knowledge, physostigmine has not been approved for human pretreatment in either the United States or the United Kingdom. Pyridostigmine bromide tablets (30 mg) are provided to United States combat units as a contingency pretreatment; one tablet is to be taken every 8 h when nerve agent exposure is imminent (Dunn and Sidell 1989).

Compounds considered for pretreatment use are powerful drugs that have toxic properties of their own. Protective exposures need to be determined by trained individuals on the basis of body weight and condition of health. In unskilled hands, damaging exposures could easily be administered (children or individuals weakened by age or illness are vulnerable here). There is an additional concern about substance abuse if uncontrolled access to these drugs were permitted.

The principle advantage of prophylactic drugs are:

1. Pretreatment by prophylactic drugs has been shown to be an effective protection against incapacitation or death induced by exposure to the lethal nerve agents GB and VX.
2. The additional protection offered by prophylactic drugs (in addition to the presumed use of protective equipment) would be an advantage to first responders, security, and emergency personnel.
3. Other individuals whose jobs required frequent trips into contaminated or potentially contaminated areas (such as police officers, fire fighters, repair crews, etc.), would also benefit.

The disadvantages of prophylactic drugs include:

1. Drug storage. Some prophylactic compounds require controlled storage conditions and may deteriorate if these conditions are not maintained. Rotation of stocks is necessary to maintain drug potency.
2. Potential for substance abuse and accidental poisoning. Valium® is a controlled substance and atropine is a hallucinogen.
3. Recommended drugs are powerful and can cause serious injury if mishandled. Need for trained personnel to provide treatment.

The Center for Disease Control (CDC) recommends that prophylactic drugs be used only by trained personnel such as emergency and medical staff (e.g., EMT, MD, RN).

## C.6 ANTIDOTES

Antidotes are used to relieve, prevent, or otherwise counteract adverse effects resulting from agent exposure. Antidotes are somewhat agent-specific in that nerve agents (as a group) require different antidotes than the vesicants.

Nerve agent antidotes (atropine, pralidoxime, and other oximes) block the effects of agent-induced skeletal and smooth muscle contraction (i.e., relieve convulsions and ameliorate loss of breathing control) and reduce glandular paralysis (i.e., dries up the copious respiratory secretions that make normal breathing difficult). These same antidotes are effective in treating cases of organophosphate insecticide poisoning (e.g., Parathion, Malathion), and the treatment protocols are based on sound clinical data for humans.

There are no specific antidotes for mustard agent poisoning; its chemical reaction with biological tissue is so rapid as to be irreversible for all practical purposes. Attempts at therapy have been aimed at rapid decontamination and symptomatic therapy to relieve the effects of chemical burns to the skin, eyes, and respiratory tract.

Exposure to the organic arsenical vesicant, Lewisite, can be effectively countered by treatment with British anti-Lewisite (BAL) after untreated time lapses of as much as 1 h. Newer, water-soluble BAL analogues that can be administered orally or by intravenous drip, are effective in laboratory animals even if provided 4 h after exposure and have been successful in treating occupational victims of heavy-metal (e.g., methylmercury, lead) poisoning. Exposure and treatment protocols for the water-soluble BAL analogues have not yet been developed in the U.S. because these compounds are considered "orphan drugs."

Combined therapy using intramuscular or intravenous treatment with atropine plus pralidoxime is more effective for treating nerve agent exposure than either antidote used in isolation. Both drugs are available as autoinjector units to U.S. military personnel. Effective exposure is primarily based on victim body weight, age, and severity of observed agent effect(s). Careful monitoring is necessary to maintain adequate exposure rate while simultaneously managing signs of antidote overdose (elevated body temperature and blood pressure, restlessness, hallucinations, etc.). In severe cases, extended treatment over days or weeks may be necessary to counteract the effects of continual organophosphate

mobilization from body storage. Other oximes, alone or in combination with Valium®, atropine, and benactyzine are part of the antidote treatment regimes in use by military services in the United Kingdom and Europe.

Repeated intramuscular injections of BAL are usually needed to treat the topical and systemic effects of Lewisite exposure. Effective exposures are, again, based on victim body weight, age, and severity of effect(s). BAL is not likely to be fatal at clinical treatment levels, but a consistent response in BAL-treated patients is a rise in diastolic/systolic blood pressure as well as rapid heartbeat. Nausea and headache are often noted and children may experience fever. Treatment should be carefully monitored by trained personnel.

The principle advantages of antidotes are:

1. Appropriate use of antidotes saves lives and reduces the severity of effects from sublethal exposures.
2. Antidote overdose is rarely fatal and does not usually generate disabling side effects.
3. Effective treatment can be performed under field conditions.

The disadvantages of antidotes include:

1. Drug storage. Some antidote drugs require controlled storage conditions and may deteriorate if these conditions are not maintained. Rotation of stocks is necessary to maintain drug potency.
2. Potential for substance abuse and accidental poisoning. Valium® is a controlled substance and atropine is a hallucinogen.
3. Recommended drugs are powerful and can cause serious injury if mishandled. Need for trained personnel to provide treatment.
4. Potential adverse effects of antidote treatment by individuals unlicensed to administer drugs is governed by "Good Samaritan" laws specific to each state. Great variability exists in the authority and protection (from lawsuit) offered to unlicensed individuals such as teachers, first aid volunteers, etc.
5. BAL treatment is of limited utility; the sole stockpile of Lewisite is reported to be comparatively small and resides at one site—the Tooele Army Depot in Utah.

The CDC's recommends that this protective action be performed only by trained individuals and only when agent exposure is relatively certain.

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# APPENDIX D

# PROTECTIVE ACTION CASE STUDIES

# APPENDIX D
# PROTECTIVE ACTION CASE STUDIES

## D. IN-PLACE SHELTER CASE STUDIES

Relatively little is known about current practices regarding the use of in-place shelter to protect people from exposure to potentially toxic chemicals. This section reports on eight case studies where in-place protection measures of some kind were used in recent chemical emergencies. Because there are relatively few cases, and because they are unique, each is described. Some comparisons and generalizations across cases are then examined.

## D.1 Case Selection

Chemical emergencies from across the nation were identified by a systematic automated search of the Associated Press (AP) and United Press International (UPI) dispatches using a data base of newspaper and periodical publications called "NEXUS". This search updates previous data (Sorensen 1987) describing evacuations resulting from chemical accidents from 1980 to 1984. The previous searches indicated that key-word searches using evacuate(d) would be used in the negative sense for cases involving in-place sheltering (e.g., not evacuated(d), no evacuation). Sorensen (1987) reports 295 chemical incidents being reported between 1980 and 1984 that involved evacuations of 10 or more people. The update of that data indicate that 557 additional chemical emergency events were reported between January 1, 1985 and September 30, 1988, for a total of 852 events reported from January 1980 to September of 1988. Figure D.1 summarizes these data for all chemical accidents. On the basis of content analysis of the news-wire articles, only 14 of these events seemed to use in-place shelter as a response to the potential exposure in any manner. Table D.1 provides a complete list of these 14 events. Preliminary screening interviews with local officials indicated emergency officials advised, recommended, or ordered in-place sheltering in only eight of these events.

## D.2 Case Descriptions

### D.2.1. Oliver Brown Trucking Company Fire

At approximately 11:45 a.m. on March 20, 1985, a fire broke out at the Oliver Brown Trucking Company warehouse in Plainfield, N.J. The first alarm was called in at 12:14 p.m.; at 12:19 p.m. the event was declared a major fire. Because some surrounding buildings were already on fire and others were endangered by radiant heat, the immediate area was evacuated and sealed off. The blaze burned out of control until approximately 5:00 p.m. A caustic gas with traces of hydrochloride was formed when polyvinylchloride pipes stored in the warehouse burned. At least 44 people were taken to area hospitals; 2 were admitted; and more than 40 were treated and later released for smoke inhalation

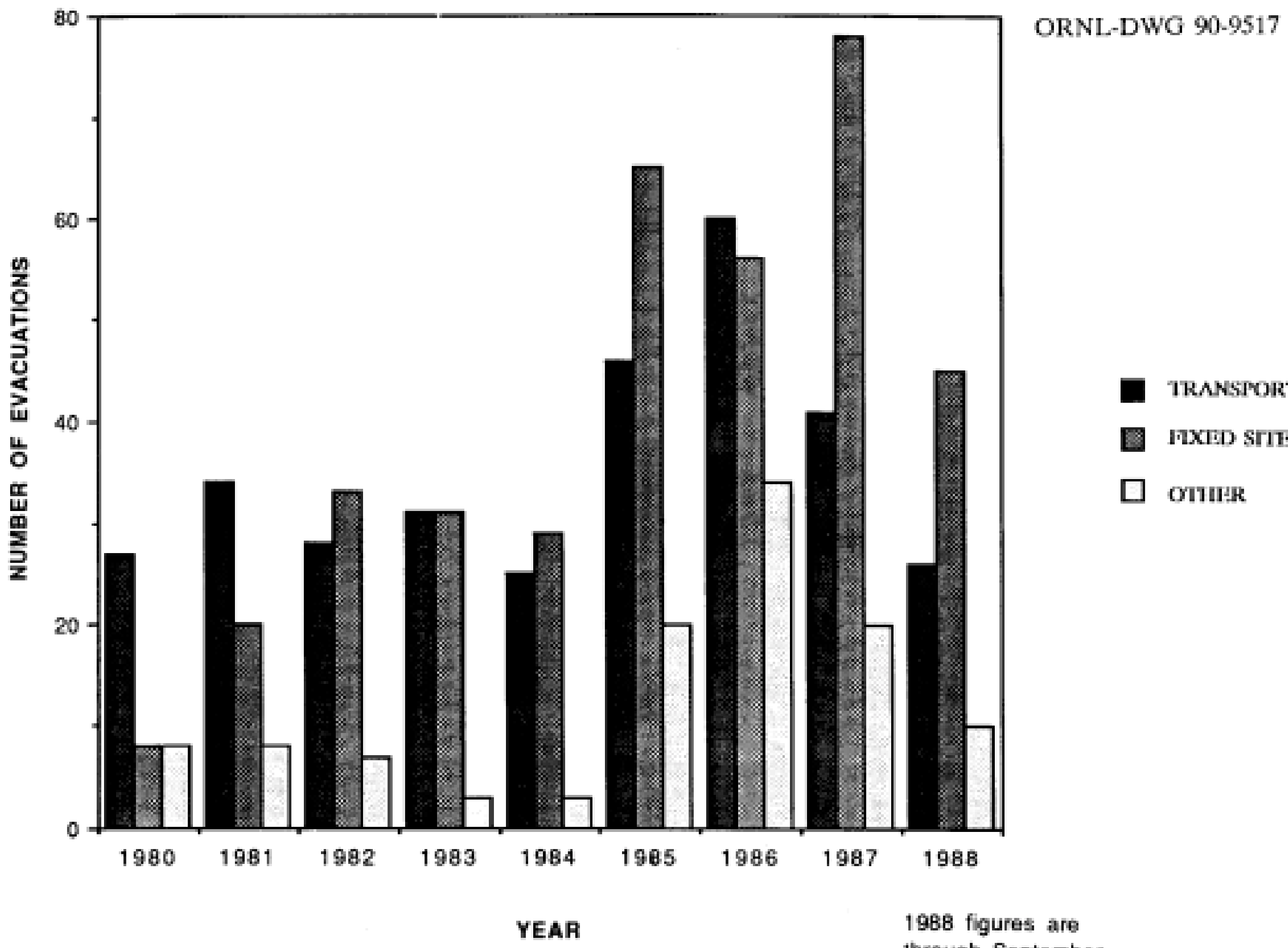


Fig. D.1. Evacuations due to chemical accidents.

**Table D.1. Selected case studies using in-place protection from chemical accidents**

| Location | Date of event | Description | Chemicals [CAS numbe |
|---|---|---|---|
| | | **Protected in-place** | |
| Plainfield, N.J. | January 3, 1985 | warehouse fire | hydrochloride [7647-01-01] |
| Hoboken, N.J. | April 13, 1985 | caustic fumes | undetermined |
| Harrisburg, Pa. | February 3, 1986 | fire at TRW | 140 hazardous chemicals |
| Lampoc, Calif. | April 18, 1986 | Titan rocket explosion | hydrazine [302-01-2] |
| Woburn, Mass. | April 23, 1986 | explosion in laboratory | trichlorosilane [10025-78-2] a hydrogen selenidel [7783-07- |
| Essex, Md. | September 12, 1986 | chemical tanker leak | sulfur trioxide [7446-11-91] |
| Richmond, Va. | June 10, 1988 | chemical tanker accident | nitric acid [7697-37-2] |
| North Chicago, Ill. | June 2, 1988 | fire at Traco | chlorine [7782-50-5], polyvin chloride [9002-86-2] and pol |
| 42-5] | | | |
| | | **Evacuation only** | |
| Olive Branch, Miss. | March 18, 1986 | suspected pesticide spill | methyl parathion [298-00-0] |
| Boone, Iowa | July 29, 1986 | train derailment | endosulfan [115-29-7], propy [115-07-1], pyridine [100-86- acids and insecticides |
| Whitesboro, N.Y. | July 29, 1986 | acid spill at Kelsey-Hayes | muriatic acid [7647-01-01] |
| Newport Beach, Calif. | February 22, 1987 | chemical plant fire | sodium cyanide [143-33-9], hydrofluoric acid [7664,39-3], hydrochloric acid [7647-01-0 |
| Somerville, Mass. | February 28, 1987 | gasoline tanker accident | gasoline [8006-61-9] |
| North Tonowanda, N.Y. | June 27, 1987 | gasoline spill | gasoline [806-61-9] |

*Available information on chemicals involved or potentially involved in emergency; Chemical Abstracts Services (CAS) Registry Numb numerical identifiers assigned by the CAS Chemical Registry System.

and elevated levels of blood gases, usually associated with exposure to burning petrochemical compounds.

Because of the caustic gas release and shifting winds, people in a 8 to 10 square-block area were advised to evacuate after approximately 2 h into the emergency. Being in a relatively high crime area of the city, many people were reportedly reluctant to leave because of the possibility of looting. People choosing to stay were told by officials to (1) close doors and windows, (2) stay inside, (3) turn off circulating fans, and (4) listen to radio or television to monitor the situation. Accounts differ regarding the amount of time people were expected to stay "buttoned-up". No official "all-clear" was indicated.

### D.2.2 Hoboken, N.J. Caustic Fumes

On the evening of April 13, 1985, a police officer in Hoboken, N.J. called for an ambulance after complaining of disorientation, respiratory and eye irritation. Another law enforcement officer trained in hazardous materials enforcement and compliance was dispatched to the scene at 9:30 p.m. Rescue squad and emergency workers lifted a hatch on the sewer system and immediately experienced eye irritation and skin rashes. Even though some of the emergency personnel were sent to the hospital, no protective equipment was used in the incident. In all, 14 emergency responders were sent to the hospital, including the lead fire department official on the scene; ten of these were admitted for overnight observation and treatment. Several potential sources of the caustic fumes were investigated, but no source was identified. The fire department used pumpers to flush the sewer system all night, with the situation being declared under control at 5 a.m. the next day.

Because of the highly irritating effects to eyes, strong odor, and obviously deleterious effect the caustic fumes were having on people in the area, police officers went door-to-door and told people to stay inside and to keep their doors and windows closed. In addition, residents in the area were told not to use water. Emergency personnel considered evacuation, but determined that in-place sheltering was their most appropriate option. This decision was reached because of (1) the uncertain source in terms of both magnitude and type of the agent, which made it unclear that evacuation could be conducted safely, (2) the inability to determine exactly where the caustic fumes would go when flushed through the sewer system, and (3) the perception that with the outdoor temperature being between 40° and 50° F most people would be inside with the windows closed.

### D.2.3 TRW Plant Fire

On February 3, 1986, fire broke out at the TRW plant in Harrisburg, Pa. The list of hazardous materials stored in the building was extensive. Specifically listed as being stored in the facility were substantial quantities of oil and liquid sodium hydroxide, diluted sulfuric and hydrochloric acid, concentrated sulfuric acid, phosphoric acid, sodium-hydrosulfite powder, and zirconium oxide powder. The fire, which burned out of control for nearly 5 h, sent a thermal column of potentially toxic smoke 300 m (1000 ft) into the

air. The fire was brought under control at 12:30 a.m., and the state of emergency suspended at 12:40 a.m.

Because of prior emergency planning, emergency personnel knew the types, quantities and locations of 95% of all hazardous materials in the burning building. They also believed they had a reasonable chance of containing the fire before it spread to hazardous materials. Moreover, because of (1) the dissipation afforded by the height of the thermal column associated with the fire; (2) the weather conditions being fairly stable with overcast skies, cold temperatures, and steady light winds from the northwest; and (3) the perception that at that time of day most people were inside and would have their windows closed, the mayor and fire chief decided to advise people via the media to stay inside. Area hospitals, nursing homes and homes for the aged were advised to shut down ventilation systems as a precaution. In addition, emergency officials and hospitals in neighboring areas were notified that there was a potential cloud.

### D.2.4 Titan Rocket Explosion

On April 18, 1986 at approximately 10:15 a.m., a Titan rocket exploded at Vandenburg Air Force Base near Lampoc, Calif. The explosion created a 2500 m (approximately 8000 ft) white-orange cloud of hydrazine rocket fuel. The plume sent 74 people to the hospital for examination, but only a few were found to suffer symptoms of hydrazine exposure. Several military vehicles and two office trailers were destroyed in the blast. The toxic cloud prompted the evacuation of two county parks, an island, and nearby offshore oil rigs. Local emergency officials waited for hours for confirmation that the blast and resulting plume were not deleterious to public health, but the only announcement issued by the Air Force was the statement that the incident was over.

The sheriff's office called the Air Force base to confirm the occurrence of air explosion but to no avail. Because telephones lines were becoming overwhelmed with calls from people trying to get information on the explosion, and no immediate threat could be confirmed, people who were able to contact the sheriff's department were told to stay indoors. School officials able to reach the sheriff's department were also told to keep students indoors and shut down ventilation systems. Emergency personnel were hesitant to make recommendations of any kind to the public due to uncertainty stemming from the lack of information about the explosion. Police, fire, and sheriff department personnel were able to gain information about the explosion by monitoring radio traffic. In addition, a part-time volunteer from the sheriff's department was able to provide basic information about the type of fuel usually used in Titan rockets. With this sketchy information the people were advised to "stay-put." The Sheriff's department set up road blocks at the west end of Lampoc Valley to prevent people from entering within 10 miles of the explosion site. Several hours later, the Air Force released a communication that a cloud of toxic hydvazine gas was moving harmlessly out to sea and posed no real danger.

### D.2.5 CVD Laboratory Explosion

On the morning of April 23, 1986, two chemical tanks exploded in a CVD Inc., research and development laboratory in Woburn, Mass. Fortunately, a simultaneous hydrogen gas leak triggered an automatic alarm at approximately 11:20 a.m. that evacuated the building. At about 11:30 a.m. an explosion blew a hole in the laboratory roof and the 911 dispatch was called. The plume emanating from the building contained hydrogen chloride, that was formed when released trichlorosilene and hydrogen selenide combined with air as it was released. Fire fighters arriving on the scene were overcome by fumes which filled the building and spread 800 m (1/2 mile) across an industrial park. Fire officials waited for intermittent winds to dissipate the airborne chemicals before entering the building. The situation was declared under control within an hour, but not before 24 people, including 11 fire fighters, 3 policemen, 7 employees, a reporter, and 2 others were sent to the hospital for fume inhalation and upper respiratory irritation. Four of these individuals were admitted for observation. Environmental Protection Agency officials arrived on the scene at 7:00 p.m., and an "all-clear" statement was issued around 9:00 p.m.

Approximately 10 min after arriving at the scene, the fire captain realized that a chemical release was in progress as people in the area were "dropping like flies." An evacuation of adjacent buildings was immediately ordered. The fire chief was apprised of the situation. People within approximately 400 m (1/4 mile) were evacuated, with people beyond that being told to stay in the buildings and to turn off air conditioning systems. The weather was a critical factor in the decision to use in-place protective measures in response to this incident. Emergency personnel indicated that the overcast sky and light rain were keeping the vapor cloud close to the ground. Presumably, getting people through the cloud would be problematic; therefore, people were asked to remain indoors until winds could dissipate the cloud.

### D.2.6 Baltimore Beltway Tanker Leak

On September 12, 1986 at around 4:30 a.m. a 3000-gallon tanker truck leaked sulfur trioxide from a valve on top of the tank near Essex, Md. Sulfur trioxide is a toxic chemical that reacts with water. A nine-year-old boy was sent to the hospital complaining of skin irritation and respiratory distress. A 4 $ft^2$ area was cleaned up with dry ice, and the interstate reopened a little after 9:00 a.m.

About 10 min into the incident, people in the immediate area were notified to evacuate by police who went door-to-door. There were few problems with people getting dressed and leaving as advised. About 30 min after the notification people approximately 800 m (1/2 mile) from the leaking truck were told to stay indoors and keep their doors and windows shut, with the air conditioning or heating systems turned off. Because winds were gusty and generally in the direction of the nearest community, in-place sheltering was felt advisable.

### D.2.7 Explosion and Fire at Traco, Inc.

On June 2, 1988, at approximately 3:30 p.m., an explosion and fire at Traco, Inc., spread to 20 adjoining businesses in the Coleman Industrial Complex in North Chicago, Ill. This industrial complex contains several paint and plastics companies manufacturing various toxic chemicals. The fire burned chlorine, polyvinyl chloride, and polystyrene. The fire was controlled about 8:30 p.m. Several hours later emergency personnel discovered the body of a man killed in the blaze; a total of 10 others were injured.

Upon arrival at the scene, fire department personnel determined that chemicals were possibly involved, and evacuated the building and the immediate environs of the industrial park. Because of (1) the high probability of chemical involvement; (2) continued secondary explosions; (3) shifting winds; and (4) clear, dry, and hot conditions, uncertainty about the potential for danger was relatively high. About 30 to 45 min into the event, there was a secondary explosion that prompted an in-place sheltering advisory for all residents in an area approximately 800 m (1/2 mile) by 1200 m (3/4 mile) downwind. People were directed to stay inside, close doors and windows, bring in pets, and turn off air-conditioning units. Hospitals in the area were notified to turn off ventilation systems and for personnel to remain indoors. The Environmental Protection Agency arrived at the scene 2 to 3 h into the event. As the results of the air quality tests became available, the extent of the toxicity was confirmed, and emergency officials decided that an evacuation was a more effective protective strategy. An "all-clear" statement was made at approximately 10:00 p.m. that advised people to wash outdoor furniture prior to use.

### D.2.8 Henrico County Nitric Acid Tanker Accident

On June 10, 1988, at 6:04 a.m., a tanker truck hauling nitric acid overturned on I-95 in Henrico County, VA resulting in the death of the driver. Initial reports indicated that there had been an explosion and fire, a fact that the first response teams could not confirm, and had already begun to snarl rush-hour traffic. While nitric acid is not explosive or flammable, it can cause burns to the skin and eyes and produce gas that can be fatal if inhaled, swallowed, or absorbed through the skin. Two policemen and a local resident were reportedly treated for respiratory problems associated with the spill. The Henrico County Emergency Operations Center was notified at about 6:30 a.m. A hazard incident team was dispatched to the scene; an initial entry was made to determine the condition of the driver and the extent of the leak. Emergency officials concluded that the driver of the vehicle was dead. The leak was minor, although the tanker had sustained substantial damage. Emergency personnel used potash to absorb and contain the leaked acid. A response plan was developed based upon the information provided by the first entry team. A heavy duty crane was used to raise the vehicle upright. A second entry team secured the leak. The tractor was removed to allow the removal of the driver, and the transfer of nitric acid to another tanker was completed at 6 p.m.

Upon arrival at the scene about 5 min into the event, fire department personnel immediately evacuated people on the interstate via school bus to a motel 2000 m (1.25 mile) away. A 600 m (2000 ft) perimeter was established, everyone within that area was

evacuated, including the occupants of one building. Weather conditions were favorable, with constant winds blowing away from the population. A worst-case scenario was developed by emergency response personnel who estimated that fewer than 1000 people could be effected by a major release during the procedure to raise the tanker upright. Nevertheless about 2 h into the accident the decision was reached to recommend in-place sheltering as a precautionary measure for those people outside the perimeter. People were advised to stay indoors, close doors and windows, and shut down ventilation systems. Emergency officials involved in the incident would like to have evaluated the need for in-place protection sooner and are looking for criteria to help them determine when such sheltering can be effective.

## D.3 Summary of Current In-Place Shelter Use

While it was not always clear who made the decision to recommend in-place sheltering, in these eight examples, it seemed to be largely the responsibility of the incident commander or the equivalent operational person at the scene. In the TRW fire, the mayor was reported to be on the scene, which indicates that he may have been involved in the response decision. One interesting factor that surfaced in these case studies is that, in some states, the local officials have the authority to recommend that in-place protection measures be used, but only the governor has the authority to order an evacuation. In nearly every case presented here, in-place protection measures were used in conjunction with partial evacuation. Generally, in-place protective measures were recommended for areas further away from the source of hazard and where chemical concentrations would be expected to be lower than in the areas that were evacuated.

Emergency personnel considered important contributing factors when determining the potential effectiveness of in-place sheltering, but no consistent criteria appeared to have been used to make these recommendations. Factors that were usually taken into account included weather conditions, population density, time of day, and uncertainty. Weather conditions were usually mentioned as a contributing factor; in some instances gusty winds and widely dissipating plumes led to the in-place recommendation. Vapor clouds hovering near the ground also seemed to foster in-place shelter decisions. While population density was mentioned as a contributing factor in several instances, it was not clear at what point density was important, or whether high population density or low population density led to in-place sheltering decisions. Time of day was mentioned as an important factor in the decision to recommend in-place shelter more often than not. It was usually mentioned as a way of indicating that people were already in-doors. It was often mentioned together with temperature to indicate that people already had their windows closed. But in almost every case the in-place sheltering advisory was affected by the amount of uncertainty involved in the emergency; emergency officials seemed to indicate that until they could determine that an evacuation was warranted, in-place sheltering was advisable. Factors not mentioned as important in the in-place sheltering decision included the extent to which the hazard associated with the chemicals involved is peak-concentration or cumulative-exposure sensitive, the ability of homes in the particular area to reduce exposure by infiltration (e.g., the leakiness of buildings in the

area), or the extent to which chemicals could be trapped in the building at the time of the recommendation.

While most of the in-place sheltering advisories mentioned staying inside, closing doors and windows, and turning off ventilation systems, none mentioned any pro-active measures such as putting damp towels under doors, taping large cracks, or covering exterior fans or vents. Most also mentioned staying tuned to radio or TV as a way of monitoring the situation. Emergency personnel have a proclivity to evacuate whenever possible. Emergency personnel seem to be saying that if the accident is bad enough to undertake the more active in-place measures, then evacuating those areas is probably a better course of action.

These case studies seem to indicate that recommendations for in-place sheltering in the event of a chemical accident are used more as a passive response than a pro-active response to the event. Five qualitative findings seem to support this conclusion.

1. Emergency personnel frequently indicated that they selected in-place protection because the situation simply was not serious enough to warrant more active responses.
2. In most cases (i.e., all except Hoboken, N.J., and Woburn Mass.), in-place protection was used in the outermost areas of the hazard zone.
3. The Hoboken and Woburn emergency personnel voiced concern that they were uncertain concerning whether they could evacuate people who were indoors without exposing them.
4. Emergency personnel indicated in most cases that time of day and outdoor temperature were important factors in their decision to use in-place shelter; the implication being that people would have already been indoors with the doors and windows closed.
5. Most decisions about in-place protection were also based on a high degree of uncertainty concerning the nature of the threat and its seriousness.

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# APPENDIX E

# WARNING AND RESPONSE CASE STUDIES

# APPENDIX E
# WARNING AND RESPONSE CASE STUDIES

A relatively weak set of empirical data exists on human behavior in chemical accidents. At the organizational level, about 20 case studies document the response of public officials to an emergency (Quarantelli 1981; 1983). Some of these studies include the warning process.

At the individual level, three events have been researched in which warning responses were documented in terms of public response time. These include the Mississauga, Ontario, accident involving chlorine (Burton et al. 1981), and two recent train derailments in Pennsylvania. Table E.1 list the date, place and chemicals involved in each case.

## E.1 MISSISSAUGA CHLORINE GAS RELEASE

On Saturday, November 10, 1979, at 11:45 p.m., a series of tank cars including one car filled with 90 tons of chlorine, four cars filled with caustic soda, a string of cdars containing propane, and three cars containing styrene derailed in Mississauga, Ontario, Canada. As the result of the derailment "...the propane cars were either ruptured or damaged, with their contents flowing off or exploding" (Burton et al. 1981:2-11). The chlorine car was punctured by the car following it, and the content of the cars containing styrene and caustic soda poured onto the tracks.

A number of local- and municipal-level emergency response agencies responded, including regional police, fire, and ambulance services. Police units in the area at the time of the accident were alerted by the light from the explosions, and three or four police units converged on the scene. The first police units to arrive on the scene reported the accident to the radio dispatcher. A constable and a detective sergeanht arrived on the scene several minutes. Within 3 more minutes, the people on-th-scene requested additional personnel, but alerting fire personnel was not necessary because of the high visibility and recurring shock waves caused by repeated explosions. Ambulance services were also alerted by the explosions, with four ambulances being dispateched to the scene within 4 min of the accident. Ambulance service personnel stationed themselves atrategicalloy around the area as no initial injuries where reported. The repeated explosions also alerted the general public; however, many converged on the area until emergencdy workers cordoned off the area within 600 meters of the accident.

Because the location of the chlorine tank car had not been determined, ti took 20 min to visually check each tank car. The search revealed that the chlorine car probably was engulfed in the jumbele of cars at the center of the derailed section of the train. After consulting with railroad officials, fire department representatives, the procedural representative, and the advisor from Ashland Chemicals, emergency officials decided to evacuate downwind areas (i.e., areas south and west of the site). At 1:47 a.m., nearly 2 h after the accident, the first official evacuation was ordered. Police were instructed to go door-to-door and tell residents that dangerous gases were on the train and advise them

Table E.1. Selected warning and response case studies

| Location | Date of event | Description | Chemicals [CAS num |
|---|---|---|---|
| Pittsburgh, PA | April 11, 1987 | train derailment | phosphorous oxychloride [10 |
| Confluence, PA | May 6, 1987 | train derailment | residues of propane [74-98-6 [7782-50-5], caustic soda [13 carbon disulfide [75-15-0], m chloride [74-87-3], chlorofor and isobutane [115-11-7] |
| Mississauga, Ontario | November 10, 1979 | train derailment | chlorine [7782-50-5], propan |

*Available information on chemicals involved or potentially involved in emergency.

to leave the area. Before the emergency was over (including the staged evacuation and reentry), approximately 250,000 people evacuated their homes.

On Tuesday afternoon, November 13, reentry began with those farthest from the accident site, and erroneous media messages led to massive traffic jams. Final reentry for those living in close proximity to the accident site began on Friday afternoon after a lengthy control group meeting. By 4:00 p.m., Friday, 18 tons of chlorine had been removed, leaving only 4000 to 5000 gallons. This led to a consensus decision by all experts that the remaining evacuees could safely return to their homes. To avoid concentration of potentially hazardous gas in homes, people were instructed to open doors and windows for 15 min to ventilate the building. Between 40 and 50 break-ins were reported upon return from the week-long evacuation.

The accident did not result in any deaths or major injuries; however, minor and temporary health effects were reported. These included eye irritations, respiratory problems, chest pains, food poisoning, various psychological and psychosomatic illnesses, existing illnesses aggravated by the experience, and various bruises, sprains, and broken bones. The total of reported injuries affected less than 1% of the evacuees. Nervousness and anxiety was reported by about 11% of those interviewed in August 1980 (9 months after the incident).

## E.2 PITTSBURGH PHOSPHOROUS OXYCHLORIDE RELEASE

On Saturday, April 11, 1987, at 12:29 p.m., a westbound Conrail freight train derailed in Pittsburgh, Pennsylvania. In the process of derailing, the westbound train sideswiped an eastbound train causing it to also derail. Four of the derailed tank cars on the eastbound train contained hazardous materials. Sparks resulting from the accident ignited a fire; however, ". . . contrary to reports circulated at the time of the accident, none of the hazardous materials ignited" (Railroad Accident Investigation Report, No. A-63-87, Consolidated Rail Corporation, Pittsburgh, Pennsylvania, April 11, 1987). Because of the involvement of hazardous materials, Pittsburgh emergency personnel initiated an evacuation when they arrived at the scene, about 20 min after the accident occurred. Some local residents in the immediately adjacent areas had already begun to evacuate. Up to 22,000 people were evacuated as the initial evacuation area was expanded to accommodate changing weather conditions (Rogers and Sorensen 1989).

The fire was extinguished by 3:30 p.m.; however, the primary concern centered around a derailed tank car containing phosphorus oxychloride. This tank car developed a crack in the dome that permitted between 30 and 100 gallons of lading to escape. Emergency response teams inserted a tennis ball in the vent pipe to prevent further release and neutralized the escaped chemicals with potash and sand. By 5:50 p.m. the affected areas had been declared safe and the initial evacuation order was rescinded.

Emergency officials planned a second precautionary evacuation for 1:00 p.m. the following day to upright the leaking tank car; however, a close inspection of the damaged tank car shortly after midnight detected continued degradation of the tank car. At 1:30 a.m., on April 12, an evacuation order was issued affecting between 14,000 and 16,000 additional residents within one-half mile of the scene. This second evacuation order was

not rescinded until 4:30 p.m. on Sunday, April 12, 1987. Approximately 25 people were treated for eye and throat irritation at area hospitals, and three people were hospitalized during the course of the accident.

## E.3 CONFLUENCE PRECAUTIONARY EVACUATION

On Wednesday, May 6, 1987, at 4:10 a.m., 21 of 27 "empty" tank cars carrying product residues (propane, chlorine, caustic soda, carbon disulfide, methyl chloride, chloroform, and isobutane) derailed in Confluence, Pennsylvania. Because tank cars carrying residue can haul up to 3% of the load, emergency officials had no way to determine the exact amount of product remaining in the cars. Upon examination of the train's manifest, emergency management officials initiated a precautionary evacuation of the 986 residents (Rogers and Sorensen 1989).

A 3-min nonstop siren blast was sounded, which primarily alerted the volunteer firemen; residents could not be expected to be aware of the siren-blast's specific meaning. At approximately 4:30 a.m., volunteer firemen and untrained volunteers began a door-to-door and portable emergency loudspeaker alert and notification. Public shelters were set up in the area's high school, and local school buses and ambulances provided transportation for those needing it. The evacuation was complete within 45 min. With the assistance of area-wide emergency personnel, two leaking propane tankers were sealed by 9:48 a.m. The chance of explosion and/or fire during wreckage cleanup prevented the evacuees from returning until 6:10 p.m. that evening.

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# APPENDIX F

# EXPEDIENT SHELTER TRIALS

# APPENDIX F
# SUMMARY OF EXPEDIENT SHELTER TIMING AND EFFECTIVENESS TRIALS

## F.1 Introduction

One problem associated with assessing the effectiveness of in-place shelter is the lack of data quantifying the public's ability to implement actions required to attain effective shelter. In the course of the present work, preliminary series trials were conducted to fill this gap in the existing empirical evidence. The amount of time it takes to complete expedient sheltering, the degree of reduced infiltration associated with each in-place shelter option, and the habitability of completed shelters were all appraised.

## F.2 Background

The effectiveness of some protective actions is primarily a function of the device itself, and there are no reasons to believe that implementation at the time of an incident will dramatically change the effectiveness of the action. For other protective actions, effectiveness is directly attributable to the performance of the individuals implementing the action at the time of the accident. For example, pressurized buildings are not very dependent on the actions of protected individuals to be effective, but expedient measures and all individual protection devices are very dependent on the ability of individuals to use them. The primary objective of this preliminary research was to determine the range of response effectiveness for protective actions involving in-place shelter. This principally involves measuring the amount of achievable exposure reduction, and the time it takes to attain that reduction.

## F.3 The Approach

A before-and-after experimental design was employed for 12 completed trials. The general approach was to estimate infiltration in a dwelling and selected room using Freon™ as a tracer gas. The most likely room to be used for chemical protection (e.g., interior, windowless) was selected by the subject using criteria provided prior to trial (see Appendix G). Each subject was provided an expedient materials kit tailored to the specific room selected and sheltering instructions which included a check list of required activities. This study design assumes that such kits would be provided before the emergency to individuals considered most likely to need them in an emergency. The experimental team monitored implementation of expedient taping and sealing measures and estimated infiltration of the whole house, interior room, and the sealed room (see sect. F.5 for details of tracer-gas methodology). Each of the 13 trials residences are located in Eastern Tennessee in the Oak Ridge-Knoxville area. The trials were conducted in the late spring and early summer months of 1989.

## F.4 Measurement

Each expedient shelter trial encompassed six areas of data collection: (1) tracer gas measurements used to estimate the amount of infiltration; (2) measuring time period completion of activities necessary to achieve a protected environment; (3) subject characteristics that might affect the subject's ability to implement or improve the procedures; (4) building and room characteristics that are considered to be related to effectiveness or timing; (5) the outdoor environmental conditions present during the trial; and (6) habitability measurements and observations in the protected environment.

### F.4.1 Pre-trial Measurement

Information concerning a number of subject characteristics was collected. Included were the subject's age, gender, occupation, self-assessed handiness, height/weight, physical condition, and education.

Room characteristics recorded were number of windows, size of room, number of doors, number of electrical outlets (including switches and outlets), plumbing fixture entrances/exits, linear footage, window size, number of storm windows, window type, and number of vents. Recorded building characteristics included number of exterior windows, number of exterior doors, type of construction (basement/foundation/slab), age of house or year of construction, basic design of dwelling (e.g., one story, two story, attic or not), extent of weatherization, room-to-wind-direction orientation, outside dimensions, construction materials, and nature of heating and cooling systems (split central heating/air conditioning).

Environmental conditions were monitored beginning in the pre-trial period and throughout the trial. Recorded meteorological conditions include outside temperature, windspeed, wind direction, general weather conditions (e.g., rain, cloudy, sunny) building orientation, barometric pressure, and relative humidity. In addition, time and date of test can be used to attain regional weather conditions and more generic information regarding meteorology on the day and time of the trial.

The infiltration characteristics of the building and room were determined without expedient shelter actions to provide a baseline measurement. Infiltration of both the whole-house and the room to be sealed were measured prior to initiation of the taping and sealing activities.

### F.4.2 Measurement During Trials

The implementation of various actions required to provide maximum protection from toxic chemical exposure were timed by the experimental team. Timed activities included shutting doors and windows, turning off heating/cooling and circulation systems, and taping/sealing a single room. During each trial a participant observer took detailed notes regarding the ability of the subject to conduct the procedures, the approaches used successfully by the subject, the approaches that led to difficulties, and the observable capabilities of the subject. The participant observer also took detailed notes regarding the

general habitability of the shelter, and any signs of subject irritability, frustration, or complaints or other indicators of reduced comfort in the shelter were recorded.

The flow rate of air into the sealed room was measured over a period of time long enough to establish the air change rate. This continuous measurement may be used to determine the effectiveness of in-place shelter implementation by means of the shelter's ability to reduce exposure to chemical concentrations present in the exterior (unprotected) environment. Temperature and humidity in the sheltered environment were continuously monitored to characterize general habitability.

### F.4.3 Post-trial Measurement

Post-trial measurements were used to attain information about the subject's perception of performance. One specific issue here was the extent to which the subject knew how well the shelter was sealed. Other measurements included the subject's perception of skills and abilities thought to be useful in the conduct of the procedures and where the subject had difficulty implementing the procedures. Each subject was asked to evaluate the procedures in terms of factors that could have made them easier or better and desirable instruction/training requirements.

## F.5 Tracer-Gas Methodology

Air infiltration rates were measured using techniques similar to those described by Nero et al. (1983). Well-mixed conditions were established for whole house measurements by opening all interior doors and operating several box fans during the measurement. Aliquots of dichlorodifluoromethane (Freon$^{TM}$) CAS No. 75-71-8 were released until the indoor concentration was stable at about 1 $\mu g\ g^{-1}$. An infrared analyzer and a data logger were used to record the relative indoor concentration in mV as a function of time. The infiltration rate was estimated from the observed rate of decay of the indoor concentration. For single-room measurements, the infrared analyzer was located outside the room, and sampling lines carried room air to and from the analyzer. The door(s) to the room were closed and any gaps were sealed with tape during the measurement.

## F.6 Summary of Findings

### F.6.1 Infiltration

The tracer gas methodology summarized above technically measures exfiltration in terms of relative concentration of experimenter-injected Freon$^{TM}$ in the sheltered environment. By continuously monitoring the decay of Freon$^{TM}$ concentration in the enclosed space, a rate of change is established. The recorded relative levels of Freon$^{TM}$, f, in the enclosed environment are consistent with a classic decay function characterized by a declining exponential curve. These data are transformed into their linear form, ln(f),

and an ordinary least squares regression fit estimates the slope, b, which is the change of air in the enclosed space. This regression is of the form

$$t = a + b \times \ln(f),$$

where t is time into the experiment, a is the beginning time or intercept, b is the rate of air change per hour (ACH), and f is the relative amount of Freon™ in the enclosed space measured in mV.

In 13 dwellings tested, 38 experiments were recorded. In each dwelling, measurements were taken of (1) whole house, (2) selected room with towel under entrance door(s), and (3) selected room after sealing. In order to determine if small leaks from the Freon™ source in the limited environment of the confined shelter would perturb the measurement of Freon™ concentration, internal and external injection methods were used on the first house. No perturbation was observed. As a precaution, the Freon™ source was sealed in a plastic container after the internal injection was completed.

In an attempt to reduce the amount of time required to test each dwelling, it was determined that the towel test was the least interesting for the purposes of understanding expedient shelter implementation. As a result, only two infiltration experiments were conducted for house 13 (whole house and completely sealed). In addition, the experiments in house 12 were aborted due to subject withdrawal.

Estimated house air exchange rates are summarized in Table F.1. The average whole house infiltration rate was estimated at 0.446, with the maximum rate being 1.59 and the minimum exchange rate being 0.105 ACH. Probably because the central room is not designed to limit airflow, the air exchange was generally higher when tested with only a towel under the door. This "towel test" can be considered the environment in which most of the activities involved in implementing expedient shelter are conducted. That is, the activities of taping and sealing doors, windows, cabinets, plumbing and electrical fixtures would be conducted within an environment characterized by a closed-up whole house and a towel under the door of the central room. The average exchange in this partially sealed room was 0.955, with a minimum of 0.210 and a maximum of 2.153 ACH. The completely sealed central room exchange averaged 0.334 ACH, with a minimum of 0.107 and a maximum of 0.580 ACH.

By comparing the "towel tests" with the completely sealed tests, an estimate of the amount of reduced infiltration in the central room achieved by taping and sealing procedures is attained. The completely sealed room averaged 45.6% of the exchange prior to sealing procedures, as measured by the towel only test. The greatest reductions were achieved in the most leaky central rooms, and the smallest reductions were achieved in the rooms with the smallest baseline exchange rate.

### F.6.2 Timing of Implementation

The amount of time to complete various actions in the process of implementing in-place shelter was measured in 6 s intervals in the course of the expedient shelter trials.

Table F.1. Air exchange measurements in Oak Ridge National Laboratory staff houses

| House ID | Air changes/h | | | Tape/Towel |
|---|---|---|---|---|
| | | Central room | | |
| | Whole house | Towel only per h | Taped only per h | |
| 1 | 1.590 | 1.420 | 0.440 | 31.0% |
| 2 | 0.830 | 0.870 | 0.390 | 44.8% |
| 3 | 0.183 | 1.090 | 0.460 | 42.2% |
| 4 | 0.420 | 0.900 | 0.540 | 60.0% |
| 5 | 0.295 | 1.210 | 0.510 | 42.1% |
| 6 | 0.520 | 0.420 | 0.160 | 38.1% |
| 7 | 0.120 | 0.220 | 0.200 | 90.9% |
| 8 | 0.130 | 0.310 | 0.220 | 71.0% |
| 9 | 0.660 | 1.220 | 0.580 | 47.5% |
| 10 | 0.252 | 2.153 | 0.293 | 13.1% |
| 11 | 0.245 | 0.568 | 0.117 | 20.6% |
| 13 | 0.105 | NA | 0.107 | NA |
| Mean | 0.446 | 0.944 | 0.334 | 45.6% |
| Standard Deviation | 0.408 | 0.540 | 0.165 | 21.1% |

More accurate timing is of course possible, but given the inability to accurately simulate the occurrence of an accelerated emergency, 0.1-min intervals were deemed appropriate. For example, most subjects walked at an accelerated pace from place to place to conduct the necessary activities; no subject was observed hurrying to the extent that there was any danger of the subject's being injured. The pace of activities was generally similar to that expected in an emergency exercise. Each activity was conducted and the time recorded; upon completion, experimental observers checked the activities for major problems that might impact the infiltration test (e.g. windows left open) these were then corrected and infiltration measured. Such oversights were rare, and subjects were found to know their own homes quite well; the most frequently overlooked activity included in Table F.2 was the turning off of the whole-house circulation system.

The amount of time it takes to close doors and windows and turn off air conditioners and heating systems is relatively small. The expedient shelter trials averaged 3.2 min, with a median of 2.8 min. The minimum time to close doors and windows was

Table F.2. Timing of in-place shelter implementation (min)*

| | House | A. Closing doors and windows<br>Exterior | Interior |
|---|---|---|---|
| | 1 | 2.0 | 1.0 |
| | 2 | 1.2 | 0.6 |
| | 3 | 2.3 | 2.6 |
| | 4 | 0.8 | 0.8 |
| | 5 | 1.1 | 1.4 |
| | 6 | 0.3 | 1.2 |
| | 7 | 3.2 | 1.8 |
| | 8 | 1.9 | 0.7 |
| | 9 | 4.4 | 1.7 |
| | 10 | 0.4 | 0.5 |
| | 11 | 2.2 | 0.7 |
| | 13 | 3.1 | 2.2 |
| Mean | 1.9 | 1.3 | |
| Standard deviation | 1.23 | 0.68 | |

Table F.2. Timing of in-place shelter implementation (min)* continued

| House | Towel | Vent | Electrical | Doors | Plumbing | Cabinets | Windows |
|---|---|---|---|---|---|---|---|
| | | | | B. Taping and sealing | | | |
| 1 | 0.5 | (2) 1.6 | 3.5 | 3.5 | | 4.5 | |
| 2 | | 2.4 | 3.5 | (2) 6.3 | 2.6 | 1.3 | |
| 3 | 0.8 | 2.2 | 1.8 | (2) 5.5 | 2.4 | | |
| 4 | 0.5 | 4.5 | 1.2 | 2.4 | 2.1 | (2) 14.6 | |
| 5 | 0.6 | 3.4 | 2.8 | 5.0 | 1.7 | 7.3 | |
| 6 | 0.2 | 2.8 | 1.0 | 1.0 | | | (3) 7.8 |
| 7 | 0.8 | 2.0 | 5.0 | 4.5 | 9.0 | 10.0 | 6.8 |
| 8 | 0.2 | 1.6 | 1.2 | 1.7 | | | |
| 9 | 0.2 | 4.0 | 1.1 | 4.3 | 2.5 | | |
| 10 | | 3.9 | | 1.1 | 2.1 | 3.8 | |
| 11 | 0.7 | 3.8 | 2.7 | (2) 5.7 | 2.1 | 4.2 | |
| 13 | 0.2 | | | 2.1 | | | |
| Mean | 0.5 | 2.1 | 2.4 | 2.9 | 3.1 | 5.5 | 4.7 |
| Standard Deviation | 0.25 | 1.08 | 1.334 | 1.29 | 2.41 | 2.88 | 2.97 |

Table F.2. Timing of in-place shelter implementation (min)* continued

| House | C. Total elapsed time A. total | B. total | A. and B. total |
|---|---|---|---|
| 1 | 3.0 | 15.0 | 18.0 |
| 2 | 1.8 | 16.8 | 18.6 |
| 3 | 4.9 | 13.1 | 18.0 |
| 4 | 1.6 | 26.1 | 27.7 |
| 5 | 2.5 | 21.2 | 23.7 |
| 6 | 1.5 | 13.8 | 15.3 |
| 7 | 5.0 | 38.6 | 43.6 |
| 8 | 2.6 | 5.4 | 8.0 |
| 9 | 6.1 | 16.3 | 22.4 |
| 10 | 0.9 | 10.9 | 11.8 |
| 11 | 2.9 | 20.4 | 23.3 |
| 13 | 5.3 | 2.3 | 7.6 |
| Mean | 3.2 | 16.7 | 19.8 |
| Standard deviation | 1.72 | 9.51 | 9.73 |

*Number of trial items completed.

0.9 min and the maximum was 6.1 min. Qualitatively, this variance seemed to be a function of the number of doors and windows and the distance between them.

The amount of time it takes to complete the taping and sealing procedures outlined in Appendix G averaged 16.7 min, with a median of 15.7 min. Of course the amount of time was directly related to the number of the taping and sealing activities required to attain the maximum seal in the room. The minimum time required was 2.3 min, but involved only the taping of a single door and electrical outlet; the maximum time was 38.6 min and involved sealing a door, a cabinet, electrical outlets, plumbing fixtures, and a window. The average time to complete sealing activities associated with various features in the selected room are presented in Table F.2. The largest contributors to the overall time to complete the required activities was the taping of cabinets, followed by windows and plumbing fixtures. These three activities alone total 13.3 min on average. Every room to be sealed for potential shelter will have at least one door, and doors required 2.9 min to complete sealing procedures on average. This might be reduced substantially by installing in advance exterior type door seals (e.g. magnetic or rubberized) on the door to the preselected shelter room. Electrical outlets and vents required just over 2 min each, with placing a towel under the door requiring the least amount of time at about 30 s.

No evidence was found to support the hypothesis that time to complete sealing activities is related to infiltration reduction. It is for these qualitative reasons that central room exchange measurements are believed to be dominated by exchange between the rest of the house and the central room.

### F.6.3 Habitability

The average adult produces about 0.5 $ft^3$ per hour (CFH) of carbon dioxide when at rest. Because people begin to experience serious loss of vitality and ability (Martin and Latham 1963) when concentrations of carbon dioxide reach 3%, precautions must be developed in planning for shelter sealing. Given these two important facts and the requirement that 10 $ft^2$ of space be provided for each shelter occupant (see Appendix G), the duration of stay before these adverse effects are experienced is estimated below. Assuming a rate of $CO_2$ production commensurate with adults resting, and 10 $ft^2$ per person with 8 ft ceilings, the time to reach adverse carbon dioxide levels is

$$\text{Time (h)} = (CO_2 \times \text{Volume}) / \text{Production, or}$$

$$H = (.03 \times 80\ ft^3) / .5\ ft^3/h = 4.8/h$$

for each 80-$ft^3$ unit in the shelter. Given slightly more activity such as walking at a slow pace, or that associated with the activities involved in taping and sealing, $Co_2$ production could increase to 1.65 CFH. This would mean that

$$H = (.03 \times 80\ ft^3) / 1.65\ ft^3/h = 1.45/h.$$

Hence, a period of occupation can be as much as 4.8 h, but failure to assume a resting position, and thereby reduce $CO_2$ production, can reduce this time to 1.45 h for each 80-ft$^3$ unit in the shelter.

During experimental trials (June and July 1989) the temperature inside the sealed room increased an average of 3.3°C, with a minimum increase of 1.6°and a maximum of 4.8°C. The relative humidity increased an average of 11.8%, with a maximum of 27.0% (from 54.2% humidity to 81.2% humidity), and a minimum of -2.0%. Table F.3 summarizes the temperature and humidity changes for each experiment where a complete seal test was conducted. Figure F.1 illustrates the average temperature in the sealed shelters increasing over time in the shelter for three groups of experiments with high, low, and medium temperature conditions.

On a more qualitative level, subjects were observed to be uncomfortably hot despite the operation of a circulation fan to attain complete mixing of the Freon™ concentrations in the sealed room. Visible signs of anxiety, such as repeated questions, agitation, and pointed discussion, were observed among subjects when experiments lasted longer than expected. This anxiety seemed to be reduced by frequent communication between those inside the sheltered environment and the experimenters outside.

**Table F.3. Measured temperature and humidity in sealed inner room**

| House | Temperature (°C) Beginning | End | Change | Humidity (%) Minimum* | Maximum |
|---|---|---|---|---|---|
| 1 | 27.95 | 32.73 | 4.78 | 33.7 | 39.6 |
| 2 | 23.90 | 27.80 | 3.90 | 75.5 | 86.4 |
| 3 | 30.20 | 33.20 | 3.00 | 53.0 | 81.5 |
| 4 | 26.08 | 28.31 | 2.23 | 47.7 | 62.6 |
| 5 | 27.50 | 29.48 | 1.98 | 59.2 | 74.5 |
| 6 | 29.70 | 34.38 | 4.68 | 53.2 | 60.5 |
| 7 | 30.32 | 32.91 | 2.59 | 57.1 | 80.7 |
| 8 | 31.51 | 34.73 | 3.22 | 51.1 | 80.7 |
| 9 | 24.00 | 28.00 | 4.00 | 76.0 | 77.0 |
| 10 | 27.62 | 30.87 | 3.25 | 71.1 | 82.6 |
| 11 | 24.61 | 26.19 | 1.58 | 66.3 | 86.8 |
| 13 | 29.84 | 33.64 | 3.80 | 38.9 | 42.9 |
| Mean | 27.8 | 31.0 | 3.3 | 56.9 | 69.3 |
| Standard Deviation | 2.6 | 2.9 | 1.0 | 13.5 | 16.5 |

*Minimum relative humidity generally occurred at the beginning of the test. In the house 13 test, the rela declined throughout the testing.

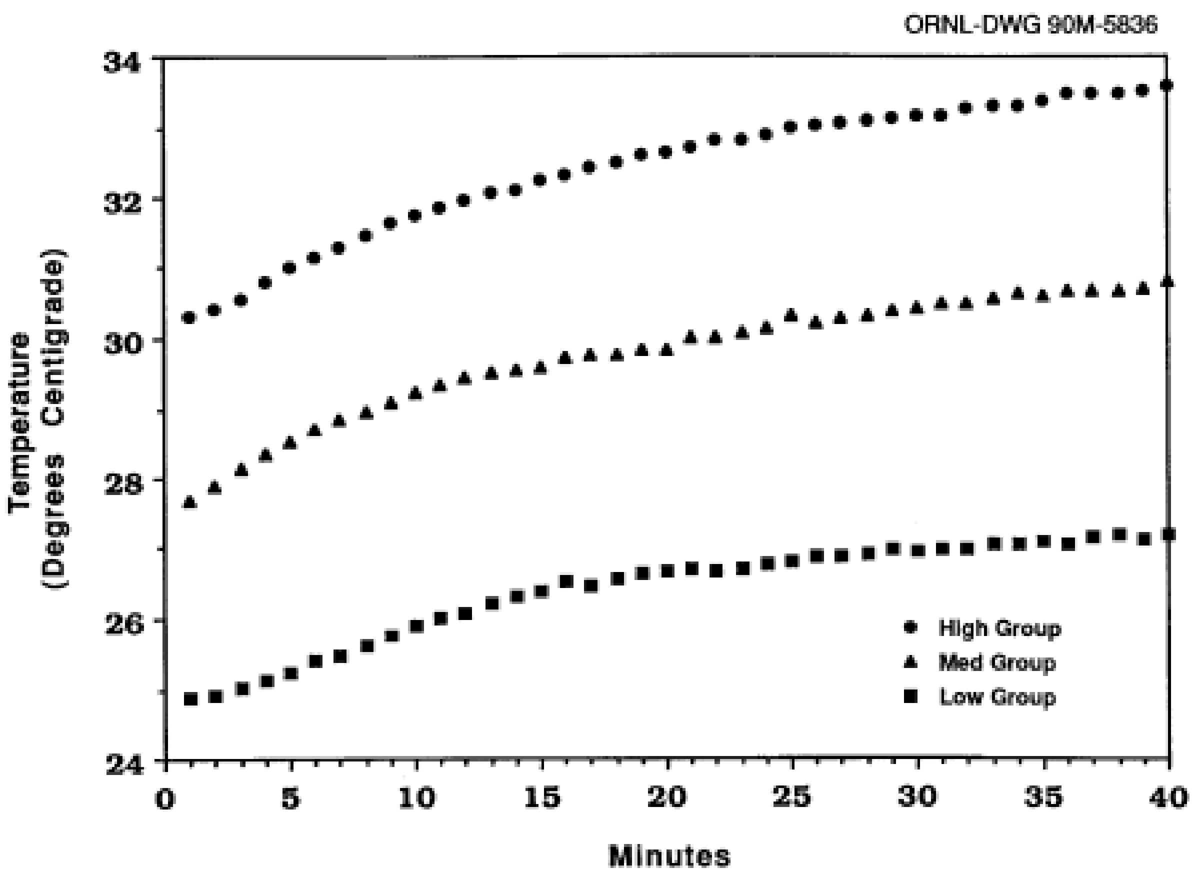


Fig. F.1. Average temperature in sealed room by time in shelter.

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# APPENDIX G

# INSTRUCTIONS FOR IMPLEMENTING EXPEDIENT SHELTER IN CHEMICAL EMERGENCIES

# APPENDIX G
# INSTRUCTIONS FOR IMPLEMENTING EXPEDIENT SHELTER IN CHEMICAL EMERGENCIES

Entering your dwelling or other buildings and following a few simple procedures can reduce exposure to released toxic chemical. These instructions can help you implement a series of actions to increase your protection. The series includes six basic steps:

1. preparing your dwelling to provide protection,
2. selecting an appropriate room within your dwelling to provide maximum shelter,
3. assembling the necessary materials needed to complete the procedures,
4. sealing a room within the dwelling to provide additional protection,
5. remaining in the shelter until notified that the hazard has passed, and
6. vacating the shelter upon plume passage.

Because each house is in some ways unique, you may need to adapt these procedures to your particular home. These instructions order the activities in terms of what is most important in obtaining maximum protection. Therefore, we recommend that you follow these steps in sequence wherever possible. Time is critically important to ensure adequate protection, so implement each step as quickly as you can without making mistakes and continue to the next step as soon as possible.

## G.1. Preparing Your Dwelling

The objective is to prepare your dwelling to provide the maximum reduction of airflow from outside to inside. These preliminary steps also provide some protection while you carry out the procedures.

- 1a. Go or stay indoors.
- 1b. Close all exterior doors and windows (close storm windows if this can be done quickly). Don't forget garage doors in integral or attached garages as well as doors normally left open for ventilation.
- 1c. Close all interior doors.
- 1d. Turn off central heat/air conditioning fans, ceiling fans, kitchen hood fans, and circulating fans.

## G.2. Selecting the Appropriate Room

The objective is to select the room that is best suited to reducing overall air infiltration while <u>having at least 10 square feet of floor area per person.</u> Under hot and humid conditions more space is advisable to avoid conditions that might lead to heat prostration within the shelter. Moreover, room air conditioners that recirculate internal

air may be used to create more comfortable shelter conditions. For example a $5 \times 8$ foot room has 40 $ft^2$, which would be appropriate for sheltering up to 4 people. This step can be completed in advance. If you have already preselected the room to provide maximum shelter, skip to Sect. G.3 below.

2a. The best room is a relatively small, has no outside walls, and is on the ground floor.
2b. If 2a is not available; select a small room with no windows.
2c. If 2a and 2b are not available: select the room with the smallest number of windows and doors.
2d. Avoid rooms with window air conditioners, windows that leak, vents to outside such as automatic dryer vents, and circulation vents.
2e. <u>Do not select rooms with exhaust vents that automatically start when the light is turned on</u>. These exhaust fans force external air into the room.
2f. If all the above elements are the same for two rooms, choose the room that is free of plumbing fixtures, because such fixtures increase the potential airflow and will require sealing as described in Sect. G.4 below.

## G.3. Assembling Materials and Resources

This stage of the procedures is designed to collect all the needed materials to reduce the airflow as much as possible in the room you selected in Sect. G.2 above. This step can be performed ahead of time. Place the following materials in the selected room.

3a. the expedient shelter kit provided;
3b. verify that the kit still has the tape, plastic sheet, scissors, clay, and screwdriver;
3c. obtain a large towel (at least bath-towel size);
3d. a ladder, stool, or chair if required to seal any ceiling vents or the tops of windows and doors;
3e. a radio or television or other communication device (preferably portable) to let you to know when the plume has passed so you can exit at an appropriate time; and
3f. if the selected room does not have plumbing, drinking water and sanitary facilities (a covered bucket or other vessel containing approximately 1 cup of chlorine bleach).

## G.4. Taping and Sealing

This set of procedures is designed to identify and seal the major sources of airflow between the room you have selected and the rest of the house, as well as restrict the flow of any toxic chemical that may be outside. These steps are sequenced to eliminate larger sources of air exchange first, so they should be implemented in the order listed whenever possible.

4a. Assemble people to be protected in the selected room and close the door. If windows were not closed as instructed in Sect. G.1 above, do so now.

4b. Jam the towel under the entire width of the door, sealing the whole area between the bottom of the door and the floor.

4c. VENTS: If there are no vents, skip to step 4d below. Locate any vents associated with the heating system, fan vents which are sometimes located in bathrooms, or vents to other rooms or to the outside such as dryer vents. Then, tape over small vents repeatedly, overlapping the tape to form a complete seal. For large vents, cut a piece of plastic sheeting large enough to cover the vent, place it over the vent, and tape the plastic loosely in place at the corners. Tape the plastic along each edge to ensure a complete seal. Repeat for each vent in the room.

4d. WINDOWS: If there are no windows, skip to step 4e below. If there are any broken or cracked windows, apply tape or cling-wrap over glass. Locate all leak points (any joints in the window frame, where movable parts of the frame come together), apply cling-wrap to each leak point. Then, cut a piece of plastic sheeting large enough to cover window and window frame, place it over the window and frame, and tape the plastic loosely in place at the corners. Tape the plastic along each edge to ensure a complete seal.

4e. Before you complete the seal on the door, check all supplies to ensure that you have enough material to completely seal the door. Do not open the door unless you clearly have inadequate materials to complete the seal; breaking the door seal will substantially reduce the protection provided by the refuge.

4f. DOOR: Tape along each edge of the door to seal off airflow, beginning with the parts you can reach from the floor and proceeding to the upper parts that may require the use of a ladder, stool, or chair. Place and tape cling-wrap over each hinge and the door handle.

4g. PLUMBING FIXTURES: If there are no plumbing fixtures, skip to step 4h below. Use putty or clay around all pipes that penetrate walls, ceiling, or floor (both intake and drainage pipes). To apply clay or putty, pull back the pipes decorative sealing ring (use screwdriver if necessary), wrap enough clay or putty around the pipe to fill any gaps between the wall and the pipe, and reset the decorative ring in clay by pressing the ring firmly against wall. Repeat for all pipe entry and exit points.

4h. CABINETS: If there are no built-in cabinets such as sink cabinets, linen closets, or medicine cabinets, skip to step 4i below. Close the cabinet doors and tape them closed according to the procedures described for doors in step 4f above. Note that, because cabinet hinges and handles are smaller than those on doors, tape will probably cover these areas adequately. Then, tape or use cling-wrap along all joints where the cabinet meets the wall. Pay particular attention to kickplates below cabinets, by checking the underside for holes and gaps. Smaller gaps may need to be plugged with clay.

4i. ELECTRICAL FIXTURES: Locate all electrical fixtures, including outlets, switch boxes, and lights. If a light is recessed or if it cannot be sealed without

turning it off, it will have to remain unsealed because covering a light without turning it off may start a fire. Put tape over the outlet boxes, and use cling-wrap or tape to cover all switch boxes. Put cling-wrap over light fixtures not in use. (Some light fixtures contain fans that run continuously with the light in the room. These fans should be turned off as early as practical; if they cannot be turned off, a different room should be selected as instructed in Sect. G.2 above.)

4j. CHECKING YOUR WORK: After, you have completed the procedures to seal the room you have selected, check each area you sealed by slowly passing your hand in front of all potential leak areas. If you can feel air flowing, try to seal it better. We do not recommend that you remove any previous seals, but you may want to add plastic sheeting over sealed areas or tape them more securely.

## G.5. Remaining in Shelter

The objective of this stage is to relax as much as possible and wait to be notified of the appropriate time to exit the shelter.

5a. Shelter occupants should be as comfortable as possible; they should stand or move around as little as possible.
5b. Remain calm and relax; doing so adds additional protection by reducing your respiration rate.
5c. Turn on communication device so you can be contacted when it is safe to exit the shelter.
5d. Ask each occupant to periodically check for airflows near them. If any are discovered, seal them by following the above procedures.
5e. Wait for notification of plume passage.

## G.6. Vacate Shelter

The objective of this step is to exit the shelter when the plume passes by and to avoid any further cumulative exposure.

6a. Put on protective clothing.
6b. Open all windows and doors.
6c. Evacuate to reception center for medical evaluation and decontamination.

## EXPEDIENT SHELTER INSTRUCTION CHECKLIST

**1. Prepare your dwelling to provide protection.**

1a. Go or stay indoors.
1b. Close all exterior doors and windows.
1c. Close all interior doors.
1d. Turn off fans.

**2. Select an appropriate room within your dwelling to provide maximum shelter, <u>having at least 10 square feet of floor area per person</u>.**

2a. Choose a relatively small room with no outside walls on the ground floor.
2b. If not available: select a small room with no windows.
2c. If not available: select the room with the fewest windows and doors.
2d. Avoid rooms with window air conditioners, windows that leak, vents to the outside, and circulation vents whenever possible.
2e. Avoid rooms with plumbing fixtures whenever possible.

**3. Assemble the necessary materials.**

3a. Use the expedient shelter kit provided;
3b. Verify that its contents are complete;
3c. Large towel of at least bath-towel size;
3d. Ladder, stool, or chair if necessary;
3e. Radio, television, or other communication device;
3f. Drinking water and covered container with chlorine bleach for sanitary purposes.

**4. Seal a room in the dwelling to provide additional protection.**

4a. Enter the selected room and close the door.
4b. Jam the towel under the door.
4c. Seal vents.
4d. Seal windows.
4e. Check all supplies; replace if necessary.
4f. Seal door.
4g. Seal plumbing.
4h. Seal cabinets.
4i. Seal electrical fixtures.
4j. Check you work; reseal where necessary.

**5. Remain in the shelter until notified that the plume has passed.**

5a. Get as comfortable as possible.
5b. Remain calm, relax, and stay immobile.
5c. Turn on communication device.
5d. Periodically check for airflows in the shelter.
5e. Wait for notification of plume passage.

**6. Vacate shelter.**

6a. Don protective clothing.
6b. Open all windows and doors.
6c. Evacuate.

# APPENDIX H

# PROTECTIVE ACTION EVALUATOR FOR CHEMICAL EMERGENCIES

# APPENDIX H
# PROTECTIVE ACTION EVALUATOR FOR CHEMICAL EMERGENCIES

PAECE is a collection of FORTRAN programs that help the user in analyzing protective action scenarios. The user interactively controls the protective action plan through each phase of its development, warning, response, and implementation. PAECE currently runs on both a PC/AT with a color graphics monitor ande EGA board and on an HP9000. Graphical display is included in PAECE to allow the user to better understand and visualize the components of a complete protective action plan. The graphics is performed by DISSPLA/PC on the PC/AT, and DISSPLA version 9.2 on the HP9000.

## H.1 PROGRAM DESCRIPTION

PARDOS and D2PC are the air dispersion models that supply PAECE with the downwind concentration results from a chemical release. The total exposure calculation by D2PC is preferred over the same from PARDOS. However, PARDOS gives a temporal distribution of concentrations that PAECE requires for protective action analysis, whereas D2PC does not give this distribution. D2PC has therefore been interfaced with PARDOS to give PAECE the best of both programs.

The chemical accident characteristics and meteorological data required to run both D2PC and PARDOS are read at the beginning of an execution of PARDOS. PARDOS then internally executes D2PC with total exposures for the scenario calculated at 100, 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000, 10,000, 20,000, 30,000, 40,000, and 50,000 meters downwind from the site of release. These distances are used because they are automatically used by an option in D2PC. The exposures at these distances are written to output file ALLDOS.RES before execution returns to PARDOS. After the user selects as many as five of the predetermined distances, PARDOS proceeds to calculate a 3 h temporal exposure distribution at each distance.

The results from D2PC are then employed. The appropriate total exposure is read from file ALLDOS.RES. The temporal distribution from PARDOS is scaled by the D2PC exposure so that the total exposure from PARDOS equals that from D2PC. See Table H.1 for a sample listing of a portion of a PARDOS.RES file from PARDOS. This file is later used in PAECE for exposure comparisons.

PAECE was written as a series of modular subroutines, any of which can later be easily changed to reflect new ideas or knowledge about a particular part of protective action. The main program is the control program in PAECE that calls all of the protective action modules. See Fig. H.1 for a chart of the modules in the order called by the main program.

**Table H.1. Sample of PARDOS listing concentrations**

| | | |
|---|---|---|
| Source strength (MG) | = | 5.971E+09 |
| Source sigma X (M) | = | 0.000E+00 |
| Source sigma Y (M) | = | 0.000E+00 |
| Source sigma Z (M) | = | 0.000E+00 |
| Time over which source is emitted (MIN) | = | 20. |
| Stability category (1-6 corresponding to A-F) | = | 4 |
| Wind speed (M/S) | = | 3.00 |
| Height of mixing layer (M) | = | 500.0 |
| Agent type | = | GB |
| Downwind distance at which exposure is accumulated (M) | = | 3.000E+03 |
| Starting exposure is to be accumulated (MIN) | = | 0. |
| Ending exposure is to be accumulated (MIN) | = | 180. |

| Time following start of Release | | | | Interval exposure | Accumulated exposure |
|---|---|---|---|---|---|
| from | | to | | | |
| HR | MIN | HR | MIN | MG-MIN/M**3 | MG-MIN/M**3 |
| 0 | 0 | 0 | 1 | .0000E+00 | .0000E+00 |
| 0 | 1 | 0 | 2 | .0000E+00 | .0000E+00 |
| 0 | 10 | 0 | 11 | .0000E+00 | .0000E+00 |
| 0 | 11 | 0 | 12 | .0000E+00 | .0000E+00 |
| 0 | 12 | 0 | 13 | .1017E-03 | .1017E-03 |
| 0 | 13 | 0 | 14 | .6080E-02 | .6181E-02 |
| 0 | 14 | 0 | 15 | .1276E+00 | .1338E+00 |
| 0 | 15 | 0 | 16 | .1062E+01 | .1196E+01 |
| 0 | 16 | 0 | 17 | .3837E+01 | .5033E+01 |
| 0 | 17 | 0 | 18 | .7078E+01 | .1211E+02 |
| 0 | 18 | 0 | 19 | .8569E+01 | .2068E+02 |
| 0 | 19 | 0 | 20 | .8836E+01 | .2952E+02 |
| 0 | 20 | 0 | 21 | .8855E+01 | .3837E+02 |
| 0 | 21 | 0 | 22 | .8855E+01 | .4723E+02 |
| 0 | 22 | 0 | 23 | .8855E+01 | .5608E+02 |

**Table H.1. Sample of PARDOS listing concentrations (continued)**

| Time following start of Release | | | | Interval exposure | Accumulated exposure |
|---|---|---|---|---|---|
| from | | to | | | |
| HR | MIN | HR | MIN | MG-MIN/M**3 | MG-MIN/M**3 |
| 2 | 52 | 2 | 53 | .0000E+00 | .1771E+03 |
| 2 | 53 | 2 | 54 | .0000E+00 | .1771E+03 |
| 2 | 54 | 2 | 55 | .0000E+00 | .1771E+03 |
| 2 | 55 | 2 | 56 | .0000E+00 | .1771E+03 |
| 2 | 56 | 2 | 57 | .0000E+00 | .1771E+03 |
| 2 | 57 | 2 | 58 | .0000E+00 | .1771E+03 |
| 2 | 58 | 2 | 59 | .0000E+00 | .1771E+03 |
| 2 | 59 | 3 | 0 | .0000E+00 | .1771E+03 |

Total Exposure = 1.7710E+02 (4.7828E+02 4.7828E+02)
(MG-MIN/M**3)

MG=milligram
M=meter
MIN=minute
S=second
HR=hour
M** =m × $10^3$ (cubic meter)
5.971E + 09=5.971 × $10^9$ (E=exponent)

ORNL-DWG M90-6913

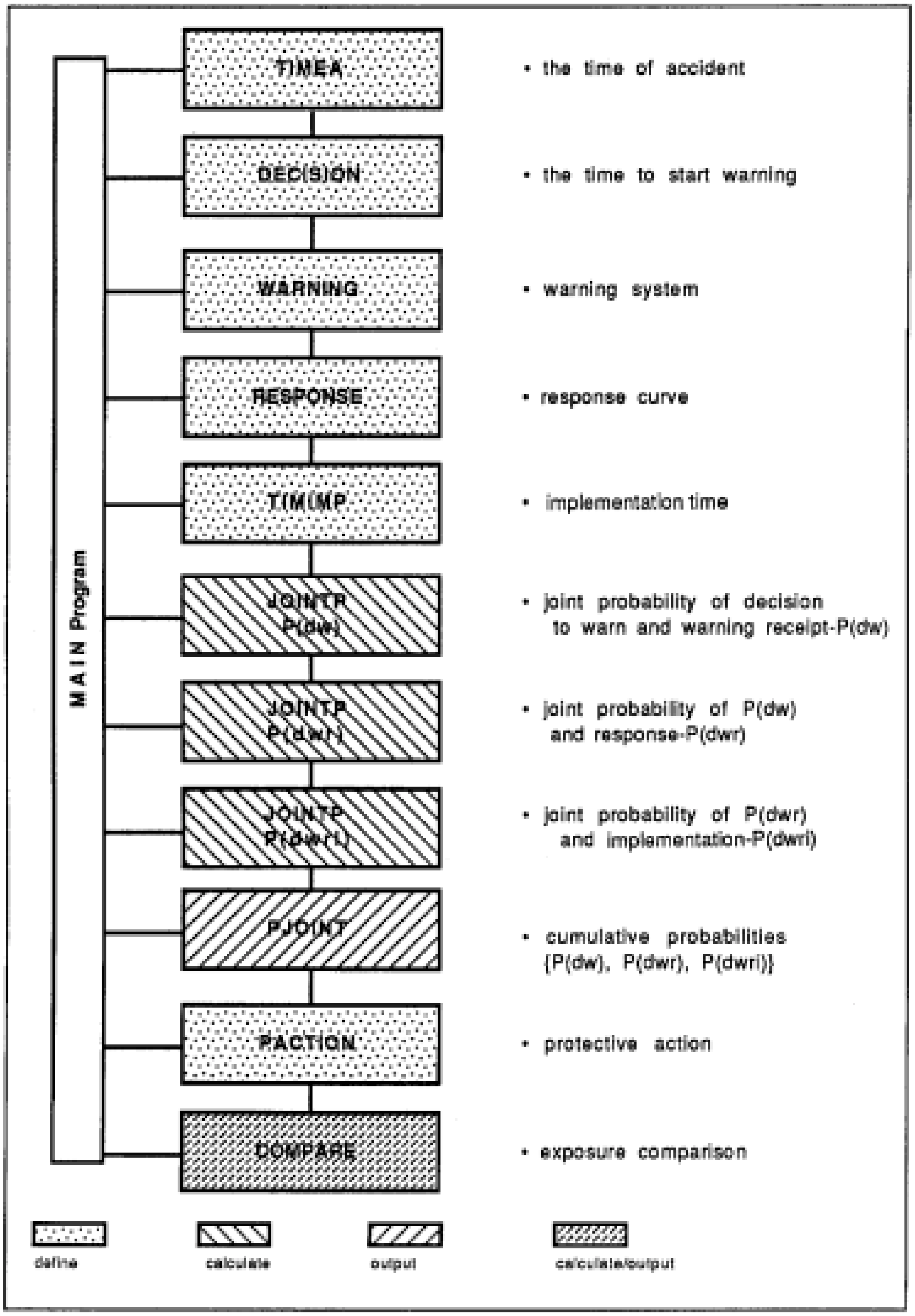


Fig. H.1. Protective action evaluator for chemical emergencies (PAECE) program sequence.

## H.2 TIMEA

The time of the accident (as military time) is defined by subroutine TIMEA. The user selects one of four ways to set the time. Below is the list of options that appears in a menu in the subroutine:

1. means stochastically derived time,
2. means most probable time,
3. means equiprobable time, and
4. means user selects the time.

If the user makes an entry that is not one of the four options, the menu reappears and the program again asks for a choice. In option 1, a "random number" generated by the computer defines the hour of the accident at a particular site. For both options 1 and 2, however, the user needs to further define the accident by answering a prompt:

1. to base time on fixed-facility accident,
2. to base time on transport accident, and
3. to base time on all accidents.

Figure H.2 depicts the accident distribution against which the random number is compared to set the time of accident.

In option 2, the maximum probability for the type of accident selected determines the time of the accident. A search is made over all the selected type of accident events, and the event with the highest probability determines the time.

For option 3, the computer-generated "random number" is compared to the sum of 24 1/24 addends to see where the random number falls. That interval determines the hour of the accident. For option 4, the user enters the time of the accident in (military time).

### H.2.1 Decision

The time delay (in minute) from the start of the accident until the decision to warn is defined by subroutine DECISION. In DECISION, the user responds to the prompt. Enter the time of the accident (military time).

After entering the time, the array of probabilities of decision to warn is filled with zeros before the time and with ones at and later than that time.

### H.2.2 Warning

The warning system is defined by subroutine WARNING. The user is given the following options for selecting a warning system.

1. sirens,
2. tone-alert radios,

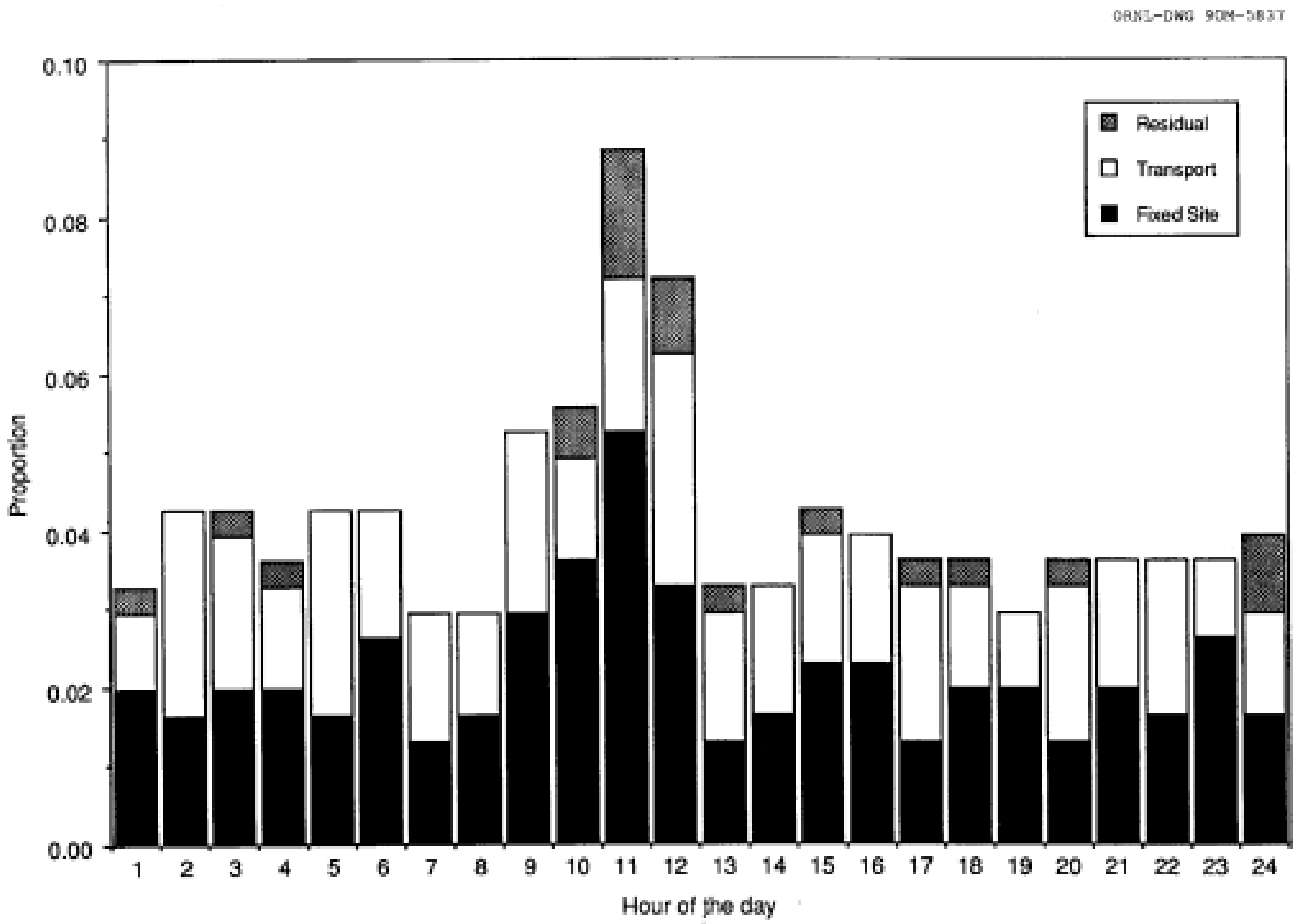


**Fig. H.2. Distribution of chemical accidents involving public evacuations by hour of the day.** Data for graph from Associated Press and United Press International Reports–1985 to September 1988.

3. media,
4. telephones,
5. sirens and tone-alert radios,
6. sirens and telephones, and
7. user specifies new parameters.

If option 7 is chosen, the user interactively must enter the warning curve parameters K, a1, a2, 30-min limit, and the release rate (%) that appear in the warning equation (described in Sect. 3.3.2). After the selection, the user is given the option to see the chosen curve along with any of the other curves. The probability of warning array is then filled with the appropriate value from the warning curve.

### H.2.3 Response

The response curve is defined in subroutine RESPONSE. The user can select from the following list of options:

1. means Confluence curve,
2. means Pittsburgh curve,
3. means average of Confluence and Pittsburgh curves,
4. means Mississauga curve, and
5. user-specified response time.

These incidents are described in Appendix E. The curves represented by options 1 through 4 can then be adjusted by a scaler defined by the user. For example, if the user wants a response that is 25% faster than the selected option, the scaler is 1.25; but should the user wish to examine the impact of a 10% slower response, the scaler entered would be 0.90. Any scaler can be used to adjust the response curves for options 1 through 4.

If option 5 is used, the response is zero until the time selected, at which time there is complete response. Response is either none or all with this option. The user is again shown graphically the selected response curve. The probability of response array is filled before returning to the main program.

## H.3 TIMIMP

The time for implementation of the protective action is defined in subroutine TIMIMP. The first thing the user does after entering TIMIMP is to select the type of protective action by responding to the following prompt:

Select the type of protective action

1. means evacuation,
2. means in-place shelter, and
3. means respiratory device.

If evacuation is chosen, the user then defines the implementation by responding to the prompt:

Select the evacuation mechanism

1. means use the clearance time (min), and
2. means use the evacuation speed (m/s).

If option 1 is selected, the user enters the time for complete evacuation. With this selection, the probability of implementation is zero before that time and one at the time and thereafter.

If option 2 is chosen, the distance from the source and average wind speed at the time of the release are read from the PARDOS result file, PARDOS.RES. The user must then enter the average evacuation speed and distance at which evacuees are considered safe. Clearance time for evacuation is then calculated from the given information.

Evacuees are assumed to be exposed to the concentration at the selected downwind distance until a set distance is achieved. This clearance time overestimates the total exposure received by the people evacuated at the leading edge of the plume but underestimates the exposure for those evacuating in the middle of the plume. If no evacuation is necessary because of the distance from the source of release, a message to that effect is written.

If the protective action is in-place shelter, the user is shown a plot of the implementation time for closing doors and windows and taping and sealing. The user then selects one of the shown implementation curves or defines the time for complete implementation. If a respiratory device provides the protective action, the user enters the time for complete implementation.

## H.4 JOINTP

Subroutine JOINTP is called three times during a run of PAECE. This routine calculates an array of joint probabilities based upon two input probabilities. JOINTP calculates the decision to warn, warning probability (PD + PW $\rightarrow$ PDW) the first time it is called. During the second call, JOINTP calculates the decision to warn, warning-response probability (PDW + PR $\rightarrow$ PDWR). The last call to JOINTP calculates the decision to warn, warning, response-implementation probability (PDWR + PI $\rightarrow$ PDWRI).

The user then is shown a plot of the individual probability curves (PDW, PDWR) as well as the cumulative curve (PDWRI) by subroutine PJOINT. This curve shows the user where time is lost during the emergency response to implement the protective action.

## H.5 PACTION

This subroutine supplies pertinent parameters for in-place shelter or respiratory device protective action. For in-place shelter, the user is shown the following list of air changes per hour (ACH) for certain houses:

- normal house has 1.5 ACH,
- weatherized house has 0.5 ACH,
- expedient shelter has 0.15 ACH, and
- pressurized shelter has 0.0 ACH.

The user must then enter an air exchange rate.

For respiratory device, the user must again supply the important parameters to PAECE. The following table of breakthrough standards appears on the screen:

Breakthrough standards for respiratory protection:

Chemical Industry—GB = 230,000 mg-min/m$^3$,

Chemical Agent Workers—GB/VX = 159,000 mg-min/m$^3$

NATO—GB = 1,500 mg-min/m$^3$, and

NATO—VX = 1,000 mg-min/m$^3$.

The user must then enter a breakthrough level. The last respiratory device parameter is the leakage rate of (around) the device. This value is entered as a fraction after the prompt.

## H.6 OUTPUT

Subroutine OUTPUT depicts the results of the protective action plan. Several curves are shown on the plot from subroutine OUTPUT that show the effectiveness of exposure reduction by the protective action plan.

The unprotected exposure values from PARDOS.RES are shown as a dashed line over the 3-h time of simulation. Dotted lines depict the exposure reduction capacity (i.e. ideal human response). A second dotted line for in-place shelters is horizontal after the incremental exposure in the shelter is greater than the incremental unprotected exposure. This line simulates vacating the shelter (perfect evacuation) and thereby receiving no more exposure.

In addition, the plot contains solid curves, which represent behaviorally adjusted protective actions. Again, a solid horizontal curve emerging from a solid curve represents perfectly vacating the shelter when the incremental exposure inside the shelter exceeds the unprotected outside exposure.

Two exposure-reduction parameters are calculated within subroutine OUTPUT. The first is an overall exposure-reduction value. This value is the following sum:

$$\sum_{i=1}^{180} \text{(1-Protected Exposure/Unprotected Exposure)/NT}$$

where NT = the number of minute within the 3 h simulation for which the unprotected exposure is greater than zero.

The second parameter, a relative exposure-reduction value, has the following formula:

$$\sum_{i=1}^{180} \left( 1 - \frac{\text{Protected Exposure - Capacity}}{\text{Unprotected Exposure - Capacity}} \right) / \text{ NT}$$

These two parameters appear on the plot from OUTPUT.

# APPENDIX I

# SOME PRINCIPLE OF IN-PLACE SHELTERING

## APPENDIX I
## SOME PRINCIPLE OF IN-PLACE SHELTERING

The protection provided by in-place shelters depends on (1) the "leakiness" or infiltration rate of the structure (expressed as air changes/h), (2) the timing of the implementation, and (3) the physiological response among human populations. The physiological response is sensitive to both the peak concentration (mg/m$^3$) and the accumulated exposure (mg-min/m$^3$). When the physiological effects associated with typical exposures are rapidly reversible, exposures may be thought of as dominated by peak concentration. Such chemicals as hydrogen chloride, hydrogen sulfide, chlorine and ammonia have toxicities that are more sensitive to peak concentrations. When physiological effects are dominated by peak exposures to chemicals, concern focuses on high concentration over fairly short durations. But when physiological response is dominated by accumulated concentration, even fairly low exposures can accumulate, if the exposure continues over a long duration, and result in severe physiological consequences. Chemicals characterized by irreversible or very slowly reversible effects, include the chemical warfare agents examined herein (e.g., tabun, sarin, mustard, and soman), and organo-metallic vapors (e.g., tetro ethyl lead). Hence, depending on the character of the chemical to be protected from, the amount of protection provided by in-place shelters is dominated by the reduction of peak concentration, or accumulated exposure, or both.

For any concentration of chemical(s) in an unprotected environment, the concentration inside an in-place shelter is a function of the concentration in the shelter at the previous time period plus the amount entering the shelter minus the amount leaving the shelter. Simply put, the concentration inside an in-place shelter may be expressed as a mass balance where accumulation accumulation is equal to input minus output. The result is that contaminants infiltrate into the reduced infiltration shelter proportional to the difference between the concentration outside and inside; and then contaminants exfiltrate from the shelter as a decay function that is asymptotic to the x-axis (see Fig. I.1). Recall the King who gave away half his wealth with each passing year, but died before his money was gone. Mass balance has a similar implication for reduced infiltration shelters; it takes longer for contaminated air to exfiltrate after the plume has passed than it did for contaminated air to infiltrate as the plume arrived.

For contaminants, such as chemical agents, that are characterized by human health consequences that are associated with cumulative exposure over time, the implication is that reduced infiltration shelters must be vacated or ventilated once the plume has passed to achieve protection. Simply put, people in reduced infiltration shelters that are not vacated enter into a trade off between being exposed to large amounts of agent for relative short durations, or being exposed to relatively small amounts of agent for relatively long durations. This appendix examines the timing of implementation, which is principally behavioral, to logically derive the key implications for the use of reduced infiltration in-place shelters; how increased exposures occur; and how minimum and maximum exposures are attained.

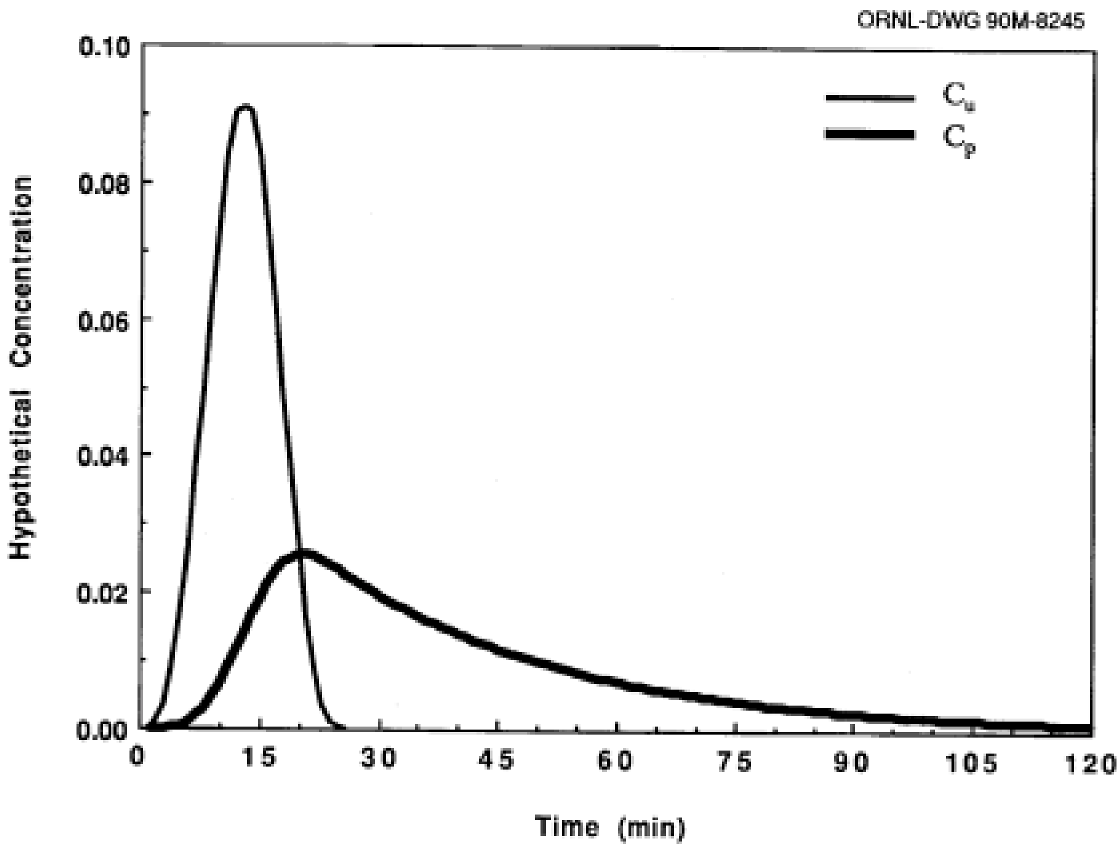


Fig. I.1. Comparison of unprotected ($C_u$) and protected ($C_p$) hypothetical concentrations when protected in reduced infiltration shelter.

## I.1. REDUCED INFILTRATION EXPOSURE

The concentration in an in-place shelter at any time, $t = n\Delta t$, is expressed as

$$C_{p_n} = C_{p_{n-1}} + I\left(C_{u_{n-1}} - C_{p_{n-1}}\right)\Delta t$$

where $C_u$ is the concentration in the unprotected environment, $C_p$ is the concentration in the protected environment, and I is the infiltration rate expressed in air changes per unit time. Graphically $C_p$ is presented in Fig I.1. As would be expected, the protected concentration, $C_p$, lags behind the unprotected concentration, $C_u$, and reaches a lower maximum (Fig. I.1). After the plume's passage, however, the protected concentration, $C_p$, remains higher than the unprotected concentration, $C_u$, for a substantial time. For contaminants resulting in physiological effects that are sensitive to peak concentrations, $C_p$ clearly represents reduced exposure. Because the maximum value of $C_p$ will always be less than the maximum value of $C_u$, in-place shelters will always offer some protection for chemicals whose physiological effect is primarily proportional to peak concentration. Hence, in-place shelters can effectively provide protection from contaminants that have physiological effects that are dominated by peak concentrations.

Exposure within an in-place shelter in situations where a chemical's physiological effects are sensitive to the accumulation of exposure may be represented as the concentration-time integral

$$Ct_p = \int_O^t C_p(t)\,dt \ .$$

which is estimated as,

$$Ct_p = \sum_{n=1}^{n} C_{p_n}\, dt \ .$$

Protection from chemical whose effect is proportional to the concentration-time integral is more complex than protection from chemical exposures dominated by health effects associated with peak concentrations. The concentration-time integrals

$$Ct_u = \int_O^t C_u(t)\,dt \ .$$

and

$$Ct_p = \int_O^t C_p(t)\,dt \ .$$

are represented as the area under their respective curve in Fig.I.1.

Birenzvige (1983) demonstrated numerically that accumulating both the protected concentration, $C_p$, and the unprotected concentration, $C_u$, for even brief durations achieves nearly the same accumulated exposure in both environments. Chester (1988) concludes analytically, for a "square-wave plume," that the Ct within a tightly sealed structure is

exactly the same as Ct outside that structure. Hence, it has been shown numerically and analytically, for sufficiently simple plume functions, that when t reaches ∞, $Ct_u$ equals $Ct_p$. It can also be shown that for a given plume at a given downwind distance, the cumulative exposure ($Ct_p$) associated with a leaky structure (i.e., I > 0) approaches the unprotected exposure ($Ct_u$) as t approaches ∞. Hence, if people remain in either the unprotected or protected environment for the entire duration of the event (from t = 0, to t = ∞),

$$Ct_u = Ct_p.$$

Birenzvige and Chester go on to demonstrate that as the infiltration rate, I, approaches infinity, the more quickly the protected exposure, $Ct_p$, approaches the unprotected exposure, $Ct_u$, and the less protection a shelter provides.

## I.2. IMPLICATIONS FOR EXPOSURE

The equal exposure means that, the outdoor concentration represented as the area under the unprotected curve, $C_u$, is equal to the area under the protected curve ($C_p$) in the example depicted in Fig. I.1. Put mathematically, if the protection is implemented at time t prior to the plume's arrival (t ≤ plume arrival time), then,

$$Ct_u \int_O^\infty C_u\, dt = \int_O^\infty C_p\, dt = Ct_p$$

In Fig. I.2 this means that the area under $C_u$ ($\Sigma\ u_i$) is nearly equal to the area under $C_p$ ($\Sigma\ p_i$). Because,

$$\int_O^t C_u\, dt > \int_O^t C_p\, dt$$

for all t after the plume arrives, and before the plume passes, moving to a leaky in-place shelter after the plume has arrived, or completing implementation of an in-place shelter after the plume's arrival will generate exposures greater than those in the unprotected environment. For all implementation times, t such that, plume arrival time, $0 < t < \infty$,

$$Ct = \int_O^t C_u\, dt + \int_t^\infty C_p\, dt > \int_O^\infty C_u\, dt\ .$$

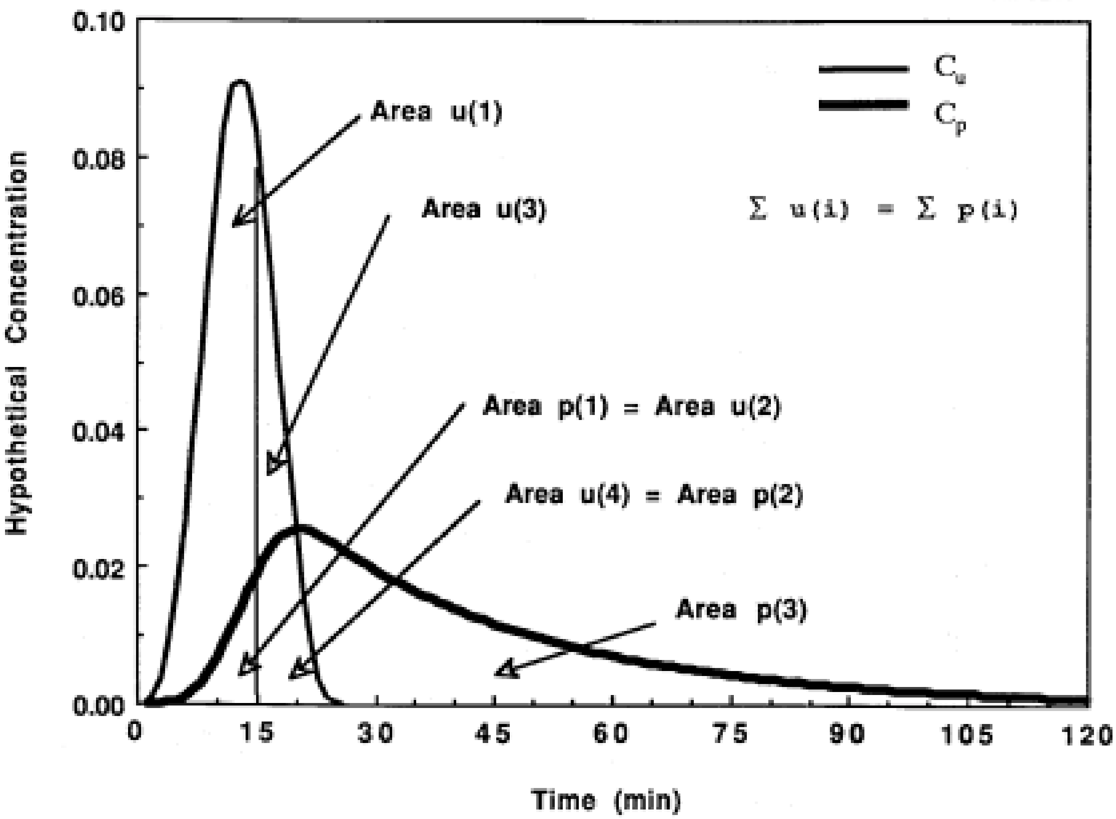


Fig. I.2. Area under hypothetical unprotected ($C_u$) and protected ($C_p$) concentrations are equal.

As in Fig. I.2, if an in-place shelter is implemented in 15 min, exposure may be represented as the sum of areas u(1), p(1), p(2) and p(3). Moreover, because the $\sum$ p(i) = $\sum$ u(i) and there are only three segments of the $C_p$ area, the exposure over the entire duration has to be greater. Let k be the time when $C_u \leq C_p$; for any time, t < k, Ct accumulates $C_u$ which is larger than $C_p$; and when t > k, exposure is comprised of $C_p$, which is larger than $C_u$. Hence, Ct will be larger than either protected or unprotected exposures alone, if the shelter is implemented at any time, t > 0.

Hence, the critical factor(s) in the use of leaky structures (ACH > 0) for protection from chemical agent plumes, or for that matter any hazardous plumes where human health consequences are associated with cumulative exposure, is(are) the transition(s) to and from the sheltered environment.

Exposure is reduced when the transition to the protected environment occurs prior to the plume's arrival, t < 0, and the shelter is vacated or ventilated once the plume has passed. That is vacating an in-place shelter at k, where $C_u < C_p$,

$$\int_O^\infty C_u\,dt > \int_O^t C_p\,dt + \int_t^\infty C_u\,dt < \int_O^\infty C_p\,dt$$

In fact, exposure is minimized if the transition into the shelter is made prior to the plume's arrival, and the transition out of the shelter is made (or ventilation is accomplished) at time t, where t = k, the point at which $C_u < C_p$,

$$\mathrm{Min}(Ct) = \int_O^k C_p\,dt + \int_k^\infty C_u\,dt \ .$$

Graphically, the minimum can be attained by tracing the curve closest to the x-axis, and finding the area under that curve (Fig. I.3). Hence, to achieve maximum protection for a given in-place shelter comprised of a leaky shelter (ACH > 0), the shelter must not only be fully implemented before the plume arrives, but the shelter must also be vacated (or ventilated) immediately when the plume passes (time k when $C_u < C_p$). This formulation under estimates Ct by the amount of contaminants (agent) introduced into the sheltered environment during entry. It is unbiased only if no agent is introduced during the transition into the shelter.

Conversely, exposure is increased when the transition into the shelter occurs after the plume has arrived, t > 0. The exposure is maximum if the transition into the shelter is made as the agent plume passes ($C_u < C_p$). The exposure is maximized if the transition to the shelter is made at the moment, k, when $C_u < C_p$;

$$\mathrm{Max}(Ct) = \int_O^k C_u\,dt + \int_k^\infty C_p\,dt \ .$$

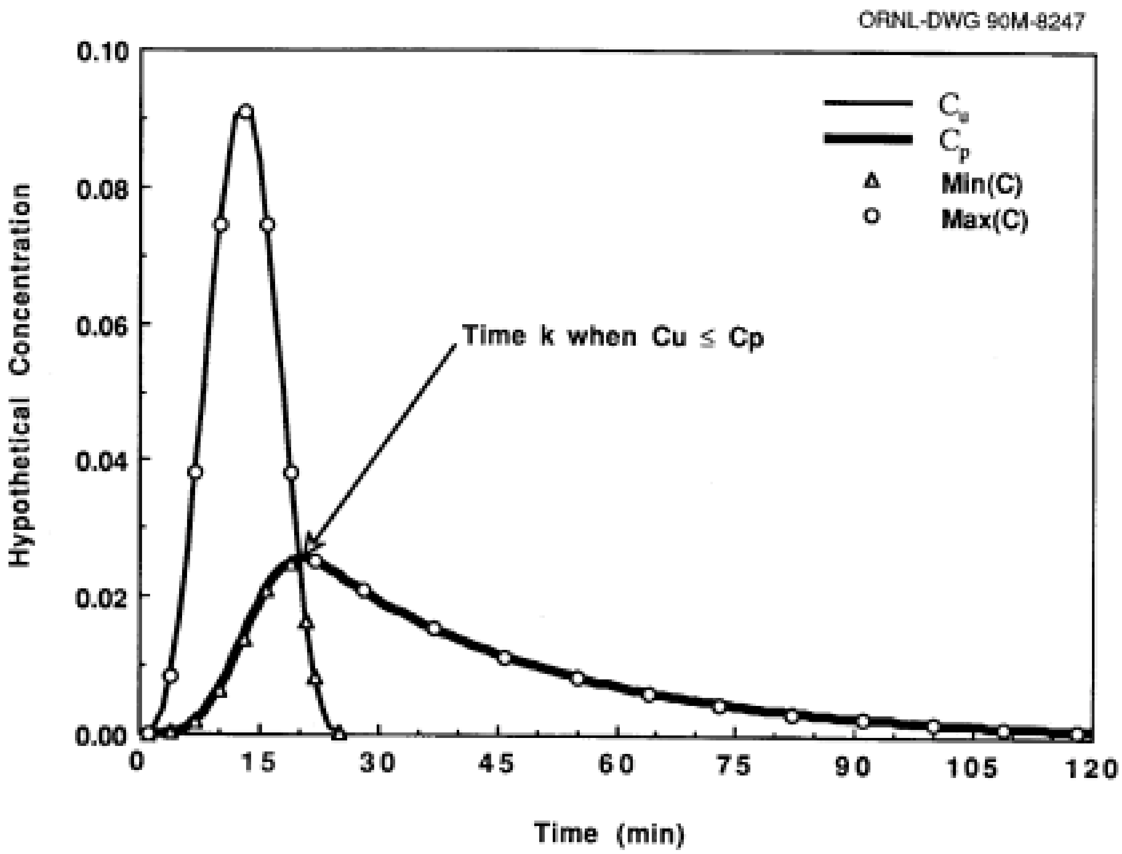


Fig. I.3. Minimum and maximum exposure compared to unprotected ($C_u$) and protected ($C_p$) hypothetical concentrations.

Graphically, the maximum is attained by tracing the curve farthest from the x-axis, and finding the area under that curve (Fig. I.3). Hence, for a population the more people that implement the shelter prior to the plume's arrival, and vacate or ventilate that shelter promptly upon the plume's passage (time k when $C_u < C_p$), the more effective the protection. Conversely the more people implementing the sheltering procedures after the plume has arrived, or failing to vacate or ventilate the shelter upon the plume's passage (time k when $C_u < C_p$), the less effective the protection.

People entering the in-place shelter just as the plume passes (time k where $C_u \leq C_p$), have already received most of the unprotected exposure, if they then stay in the shelter for any substantial amount of time they will also accumulate most of the protected exposure. Assuming a constant infiltration rate, such people could nearly double their exposure. Exposure in such instances is proportional to the area under either curve (the maximum), which is twice the area under either curve minus the overlap. Because the overlap area becomes smaller, (1) as the infiltration rate, I, becomes lower, and (2) when the plume passes quickly, the amplification of exposure will approach twice the unprotected exposure as a limit. However, this assumes that the infiltration rate remains constant throughout the event.

In reality the infiltration rate, I, probably varies throughout an emergency. Of particular interest is the infiltration rate during entry into the sheltered environment. For all times after the plume's arrival and prior to the plume's passage, t = 0 to k, because $C_u$ is greater than $C_p$, entering a shelter increases the concentration in the protected environment. Conversely, opening the shelter for any reason after the plume's passage, $t \geq k$, decreases the contamination in the shelter. Hence, entering the shelter during the plume's impact in the unprotected environment, t = 0 to k, can dramatically increase the concentration at the moment of entry, and then decay at the rate of infiltration, I. Conceptually the worst case would be to enter an unsealed shelter at the moment when the concentration in the unprotected environment is highest, $\max(C_u)$, and reduce infiltration to zero by sealing the shelter perfectly. This action sustains the maximum concentration in the shelter for a very long duration. Graphically is would be represented by a curve parallel to the x-axis (I = 0 leading to no decay), extending from $\max(C_u)$. This situation is characterized by exposures proportional to the maximum exposure in the unprotected environment, and the duration people remain in the shelter.

## I.3. SUMMARY OF IMPLICATIONS FOR IN-PLACE SHELTERING

For human health effects associated predominently with cummulative exposures, the important implications of in-place shelters in response to chemical hazards stem from the findings of Birenvige (1983) and Chester (1988). Specifically that the cumulative exposure, Ct, within a leaky (ACH > 0) structure is exactly the same as Ct outside that structure, when the structure is not ventilated or vacated after the plume has passed. Because cummulative exposures in the protected and unprotected environments are equal, $Ct_p = Ct_u$, for t = 0 to $\infty$, with longer durations exactly compensating for the reduced (minute

by minute) concentrations, reduced infiltration shelters:

- only provide protection if ventilated after plume passes, and
- are ineffective for long duration plumes, or continuous releases.

The implications for an emergency response system are understood more fully by examining the relationship between the timing of implementation and exposure. Exposure may be increased in a reduced infiltration shelter, if they are not

- fully implemented when the plume arrives, or
- ventilated as the plume passes.

The maximum exposure is attained when the sheltering process is completed just as as the plume passes (time k when $C_u \geq C_p$).

Conversely rapid implementation can achieve exposure reduction only if the sheltered environment is vacated or ventilated after the plume passes. Given that a reduced infiltration shelter environment is vacated or ventilated after the plume passes, the more quickly it can be implemented the better the chances of reducing exposure. Protection is maximized if implementation is completed prior to the plumes's arrival and vacated immediately upon its passage.

Generally, the greater the infiltration rate associated with a reduced infiltration shelter, the less protection. This occurs because,

- the concentrations in the protected environment reach higher levels, and
- ventilation must be more precisely timed to avoid exposure.

Finally, to the extent that shelters are sealed (ACH = 0) during the onset of a plume ($0 < t > k$), they can seal agent concentrations in the sheltered environment with the occupants and thereby increase exposure. Fortunately, pressurized shelters usually operate on an exfiltration principle that creates a pressure from the inside by maintaining a flow of fresh (non-contaminated) air into the shelter. This exfiltration flow would exhaust any concentrations of agent in the sheltered environment at a rate equal to the exfiltration rate.

## REFERENCES


Birenzvige, A. 1983. *A Model to Predict the Threat of Exposure to Chemical Warfare Agents in Enclosed Spaces*. Chemical Systems Laboratory, U. S. Army Armament Research and Development Command, Aberdeen Proving Ground, MD.

Chester, C. V. 1988. Technical Options for Protecting Civilians from Toxic Vapors and Gases, ORNL/TM-10423, Oak Ridge National Laboratory, Oak Ridge, Tenn.